Institute of Vehicle System Technology
Rail System Technology
Prof. Dr.-Ing. Peter Gratzfeld

Bachelor Thesis

Investigation and Classification of Bogie Designs and their Potential to Adopt Lightweight Structures by Means of a Database

Molina Fandos, Marc

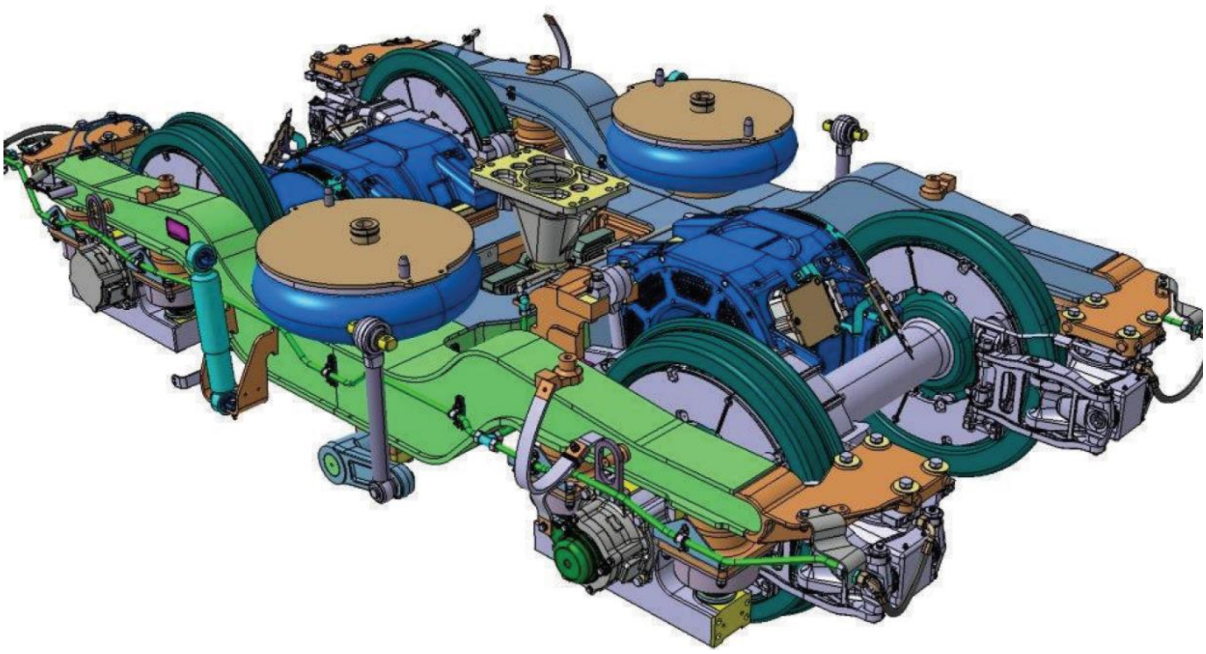

Figure 0-1: CL 606 by Alstom. Bolsterless [16, p. 16]

Project manager: M.Sc. Felix Haupt

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Matr.-No.: 2139140

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Definition of task

for

Molina Fandos, Marc

(Matr.-No.: 2139140)

Investigation and Classification of Bogie Designs and their Potential to Adopt Lightweight Structures by Means of a Database

Background

Lightweight construction is of increasing importance for rail vehicle construction. Precisely a mass reduction of the bogie components promises, in addition to an increase in load capacity and energy saving during operation, improved dynamic properties of the rail vehicle. One possibility for mass reduction is a fiber composite metal hybrid design of rotationally symmetrical components.

In order to make the best use of the potential of this type of construction on suitable components, a good knowledge of the bogie concepts and their components, which have been developed, is of great interest. A database facilitates the organization of this knowledge.

Task

- Selection of a suitable database architecture
- Investigation of the bogie designs on the market including distribution
- Highlighting of advantages and disadvantages of each design
- Investigation on other bogie designs without a market breakthrough
- Selection of a suitable classification of the designs with regard to their properties
- Identification of suitable components for fiber composite metal hybrid construction

Declaration of Originality

I hereby formally declare that I have written the submitted thesis independently. I did not make use of any outside support except for the use of the quoted literature and the sources mentioned in the paper. Furthermore, I assure that all quotations and statements that have been inferred literally or in a general manner from published or unpublished writings are marked as such. I am aware that the violation of this regulation will lead to failure of the thesis.

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Karlsruhe, 09.02.2018

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First of all, I would like to thank M.Sc. Felix Haupt for agreeing to supervise my thesis. It has been a pleasure to work with him for his ideas, suggestions and support at all times, but primarily, for motivating me when I needed it.

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All the new friends that I have made in this Erasmus adventure also deserve special mention in this acknowledgment part because without them, it would have been more difficult.

Abstract

The willingness to get lighter vehicles to reduce pollution to the atmosphere has never been so high. It is also present in the railway world, both in the body of the train and in the bogie. This thesis has been focused on bogies. There is a great variety of bogies, each one looks for specific properties depending on the application that is going to have. In general terms, it is difficult to differentiate the parts of each bogie, to understand why one uses a type of suspension rather than another type for example.

To clarify this issue, a broad classification of bogies components designs is carried out, furthermore, a general analysis of each component design has been added to the classification, highlighting its advantages and disadvantages.

To compact and sort all this information, a database has been created using the structure of the previously selected classification. The engine of the database is the program *Microsoft Access* in its 2016 version. Through queries, forms and reports will be possible to analyze the market situation. Moreover, get an overview of how the components are arranged and selected for the bogies. The created database is a tool that can be extended, improved and adapted to the requirements of a future user.

Finally, in this thesis, the database has been filled with 74 bogies from important and worldwide manufacturers such as *Alstom*, *Siemens*, *Bombardier*, among others. Queries have been done to demonstrate how the database works, but also, to answer questions that have arisen during the creation of this thesis.

Contents

1 Introduction

1.1 Motivation

The desire to reduce the weight in vehicles is also present in the railway world, this improves the dynamic behavior of the vehicle but also reduces the energy needed to drive it. Focusing on the bogies and their components, it is necessary to have an overview of their components, understand how they work and know the other possible designs that fulfill the same function. Once all the parts and possible designs of the bogies are known, it will be possible to study which part could be replaced by fiber composite metal hybrid parts to achieve weight reduction.

The analysis and classification of the components designs will help future research focused on one of these designs and therefore, achieving weight reduction. On the other hand, a database is a perfect tool to organize and give an overview of how the bogies are currently in the market, likewise, to know how the components are arranged in the bogies.

1.2 Objective

The aim of this thesis is the creation of a suitable classification of bogies designs regarding their properties, analyze these designs to find their advantages and disadvantages, and finally use this classification as a structure to create a database.

The database must be able to save the technical information of all kinds of bogies from the market by classifying their designs using the pattern created in the classification. Though queries, forms and reports, the database should provide information about the bogies saved. Establishing a common pattern for the nomenclature of designs is an important aspect, manufacturers can designate different names for the same design. This leads to a difficulty in filling in the database.

To gain an insight into the market penetration of bogies, aspects such as country where the bogies operate, penetration in the market and users of the bogies, must be present in the database.

1.3 Outline

For the successfully achieving of the objectives explained above, a research work through books and railway articles is carried out. A comparison between diverse sources gives a general overview of the properties of each design. To get closer to reality, technical information from university reports have been also analyzed and added to the comparison. The aim is to provide a practical and not only theoretical point of view of the behavior of the different components.

Before the creation of the database, it is necessary to develop the classification pattern. Secondly, 5 tables have been created where the different components analyzed are grouped by subjects. Besides, technical data sheets of the main bogie manufacturers have been searched and added to the database. Lastly, 5 queries have been created to corroborate its operation, furthermore, in these queries, were extracted results that help to understand certain designs mentioned in the classification.

2 Previous knowledge

In the explanations of this thesis, technical vocabulary is used. To make the reader easier to understand, even if it is not familiar with technical vocabulary. Basic concepts and technical words used within the thesis are defined in this chapter.

2.1 Basic definitions

- Bogie: in the railway world, a bogie is a framework carrying wheelsets. It is located under the carbody and its function is to drive it along the rails.
- Jacobs bogie: is a type of bogie located on between two cars from a train.
- Track gauge: is the distance between the two wheels from the same axle, corresponding to the distance between the inner sides of the rails.
- Carbody: is the wagon structure.
- Axleload: is the maximum weight that an axle is designed to support.

The next figure shows an example of a bogie where basic parts can be recognized and located. Not all bogies have the same parts, and there are missing parts in this figure, but it is a good example to have a first overview.

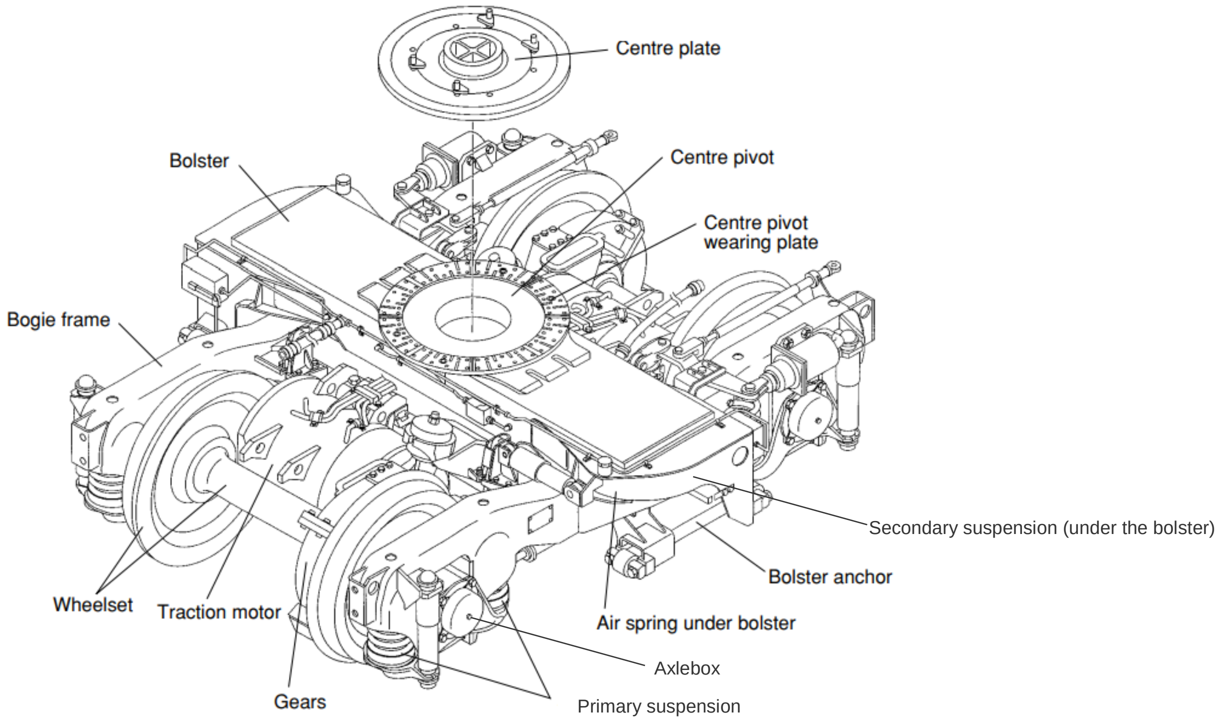


Figure 2-1: Bogie main parts [1, p. 57]

The following parts from the Figure 2-1 need a special mention:

- Bolster: is a beam that joints transversely the two sides of the bogie. It is normally placed above the secondary suspension. The mechanism responsible for transmitting longitudinal forces is normally located on the bolster, as happens in the Figure 2-1.
- Primary suspension: is the suspension located between the axlebox and the bogie frame. Its main function is the isolation of the bogie frame from dynamic loads produced by track irregularities [2, p. 65]. It can be considered an analogy to the flexibility provided by the tires on a car. Because a train has steel wheels, that cushion is provided by the primary suspension.
- Secondary suspension: is the suspension system located between the bogie frame and the carbody either through a bolster and bolsterless, normally in the center of each side of the frame. Its function is to isolate the carbody from the vibrations and movements from the bogie. [3, p. 9]
- Axlebox: is housing the wheel axle bearings. It is also where the springs from the primary suspension are located.
- Bogie frame: It is essentially the bogie chassis. It is, in most cases, a steel structure.

2.2 Relative movement

The following figure relates the vocabulary used to explain movements and the motions in three axes reference. This Figure 2-2 establishes a reference pattern that will be used within the thesis.

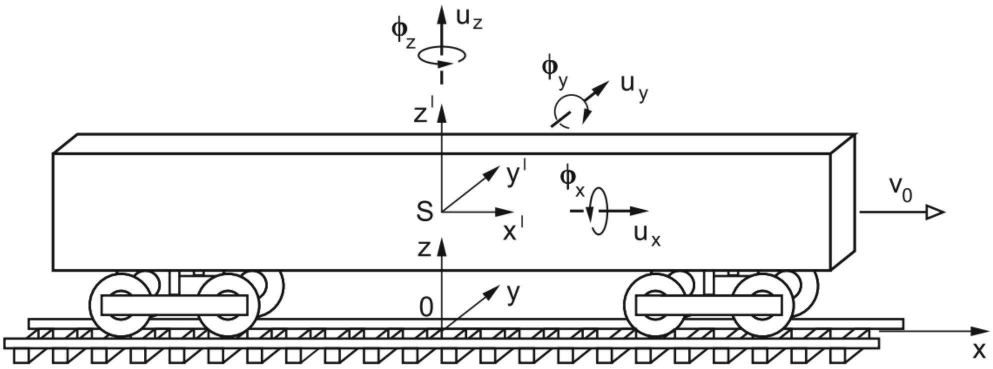


Figure 2-2: Coordinate systems; nomenclature of motions [4, p. 18]

u_z vertical motion

u_y lateral motion

u_x longitudinal motion

ϕ_z yawing

ϕ_y pitching

ϕ_x rolling

3 Components and designs analyzed

The behavior and characteristics of a bogie are mostly influenced by its components, it is important to know what features each component has and know the possible variants of each component. Depending on the component chosen for a function, the bogie will be given a specific feature and will specialize in a concrete use. There are designs of components that are typical of a type of bogies and there are others that can be seen in bogies with different applications since it has no disadvantages. In this chapter, these components and their variants are explained.

3.1 Braking system

The principal function of the braking system is to reduce the speed of the train. The weight, axleload and maximum speed are decisive parameters when choosing one of these systems. Braking can be can be achieved by the systems explained in this subchapter which are classified in the Figure 3-1.

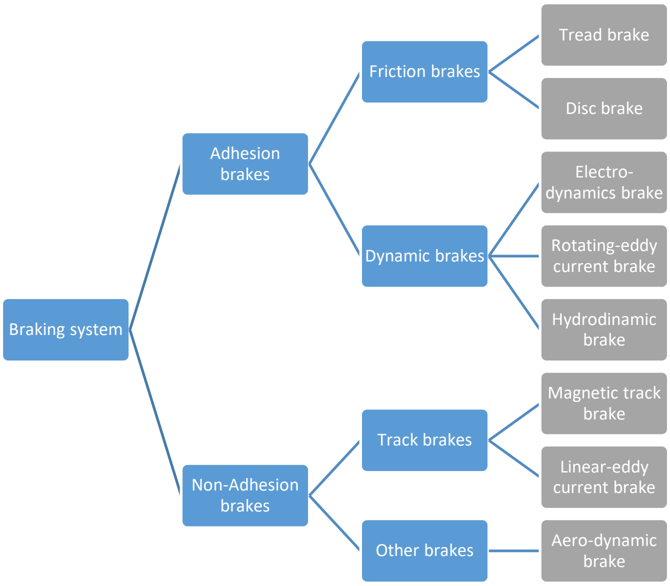


Figure 3-1: Braking system classification

3.1.1 Tread brakes

Mostly used in non-tractive units, this brake uses the friction between a brake shoe and the running surface of the wheel to create braking force. The wheel has to be designed to evacuate the heat and avoid thermal overstress. The main problem of this system is the considerable wear that occurs on the wheel. Over the time this system has been replaced by disc brakes, however, these braking systems still used in freight bogies. [1, p. 58]

3.1.2 Disc brake

The braking effect is created by the friction of the brake shoe on the brake disc (Figure 3-2). There is produced a transformation of the energy into heat and it is removed via cooling fins. The most common designs are ventilated axle-mounted brake discs. This system is the most common braking system used in all the bogies due to the simplicity and good braking power which can be increased just adding more discs in the same axle as needed. [5, p. 56]

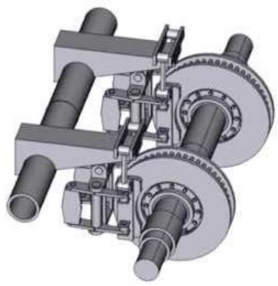


Figure 3-2: Two disc brakes mounted on the axlebox [6]

Disc brakes can also be mounted on the inner part of the wheel saving space on the axlebox (Figure 3-3). The system is called wheel-mounted brake discs. These are usually low-maintenance disc to reduce the life cycle costs. [7, p. 61]

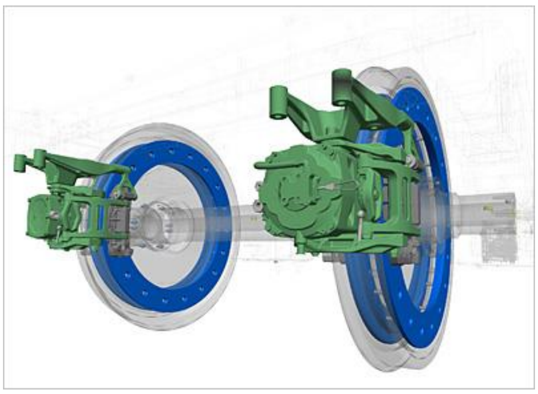


Figure 3-3: Wheel-mounted disc brake [8]

3.1.3 Electro-dynamic brake

This system consists on using an electric traction motor as a generator when slowing the vehicle, it is understood that is a brake for electric tractive units. The drive motor switches on and turns generators during the braking, transforming kinetic energy of the train into electrical energy. This is a wear-free braking system and it's very effective at high speeds. It is assumed that the motor bogies integrate this type of brakes. [5, p. 54]

3.1.4 Rotating-eddy current brake

Consists of a conductive non-ferromagnetic metal disc attached to the axle, with an electromagnet with its poles located on each side of the disk, so the magnetic field passes through the disk (Figure 3-4). The electromagnet allows the braking force to be varied. This system is wear-free due there is no physical contact between the poles and the disc. [9, p. 45]

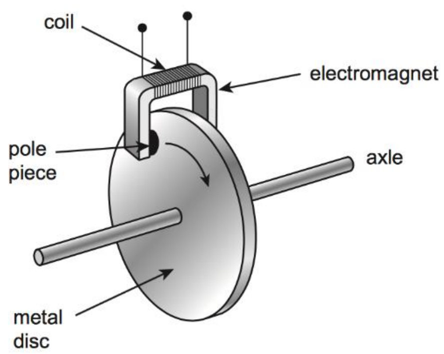


Figure 3-4: Rotating-eddy current brake [10]

3.1.5 Magnetic track brakes

This system consists of two brake shoes magnetically attracted to the rails generating friction directly on them (Figure 3-5). When using a sintering friction material, the maximum speed at which this brake can be applied is up to 350 km/h. This system is powerfully braking but causes considerable wear, which is why this system is mostly used for emergency brake applications. [11]

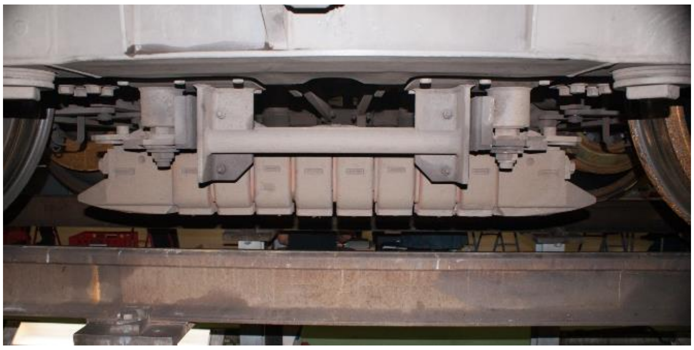


Figure 3-5: Magnetic track brake [12]

3.1.6 Linear-eddy current brake

Following the same principle of the rotating-eddy current brakes, now the electromagnets are lowered down the bogie frame, only a few *mm* over the rails. The brake force is created by eddy currents and their magnetic fields interacting with the rails (Figure 3-7). They are mostly used in high-speed bogies as service brakes in cooperation with electro-dynamic brakes. This system is wear-free due there is no physical contact between the coils and the rails. [5, p. 59]

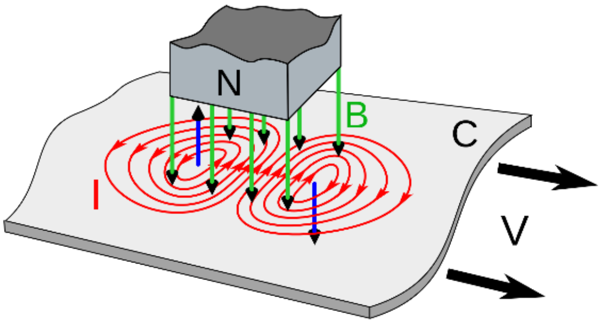


Figure 3-6: Magnetic fields and forces in linear-eddy current brake [13]

Figure 3-7: Example of a linear eddy current brake [14, p. 14]

3.2 Carbody connection

The efforts generated by the bogie to pull or brake the train must be transmitted to the carbody. This is done through the systems discussed in this subchapter. The carbody connection is not only a point of union between the bogie frame and the carbody, but it is the connecting link through which all the forces are transmitted. The possible systems are classified in the Figure 3-8.

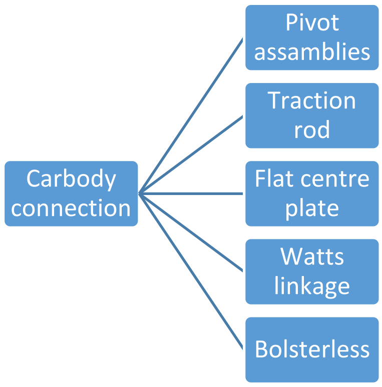


Figure 3-8: Carbody connections

The designs generally attempt this connection as simple as possible using as fewer elements as possible and reducing the elements that work on friction. [15]

3.2.1 Pivot assembly

The pivot assembly transmits traction and braking forces from the bogie to the carbody, moreover, is the point about which a bogie undergoes rotational movement in the horizontal plane to the carbody (Figure 3-9).

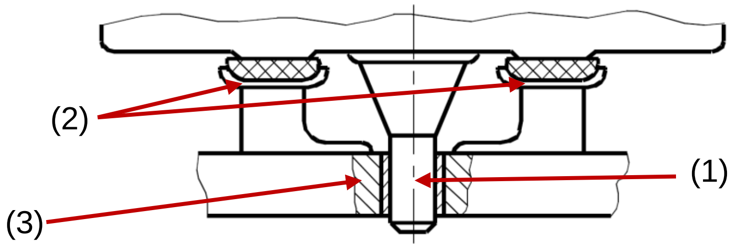


Figure 3-9: Scheme of a pivot. Pin (1), sliding plates (2) and pivot yoke (3) [2, p. 62]

According to their relative position, pivot assemblies can be classified into two types:

- High location of the pivot point: the forces transmitted to the carbody are located above wheelset in the horizontal plane as shown in the Figure 3-10.

- Low location of the pivot point: the forces transmitted to the carbody are located below the wheelset in the horizontal plane as shown in the Figure 3-11.

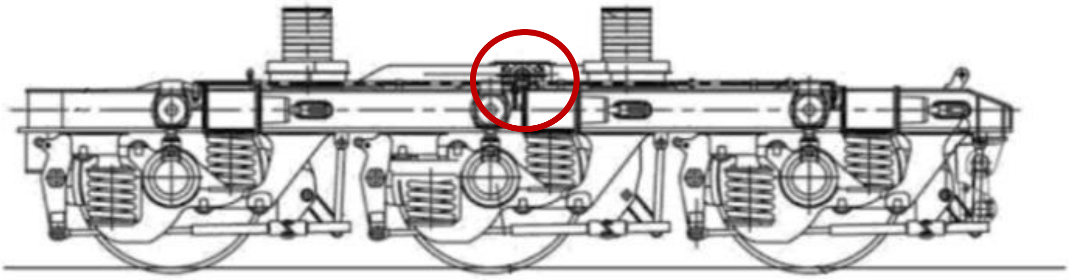


Figure 3-10: High location of the pivot [15]

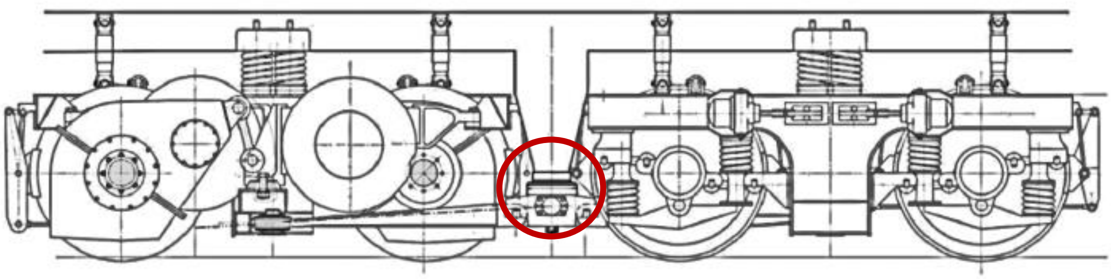


Figure 3-11: Low location of the pivot point [15]

The low location of pivot point achieves higher values of tractive and brake efforts on a bogie than another with the same design but a high pivot point.

Pivot assemblies can be designed with additional gaps that allow some small motion in the horizontal plane.

The ones with spherical joints allow the bogie to carry out a rotational movement. In addition, these can have movement in the vertical plane and partial displacement in the horizontal plane.

From the design point of view, the pivot assembly consists of a pin rigidly fixed to the bogie frame on one end, while, on the other end, a pin is inserted in the pivot yoke which is fixed to the frame of the bogie or the bolster as shown in the Figure 3-9.

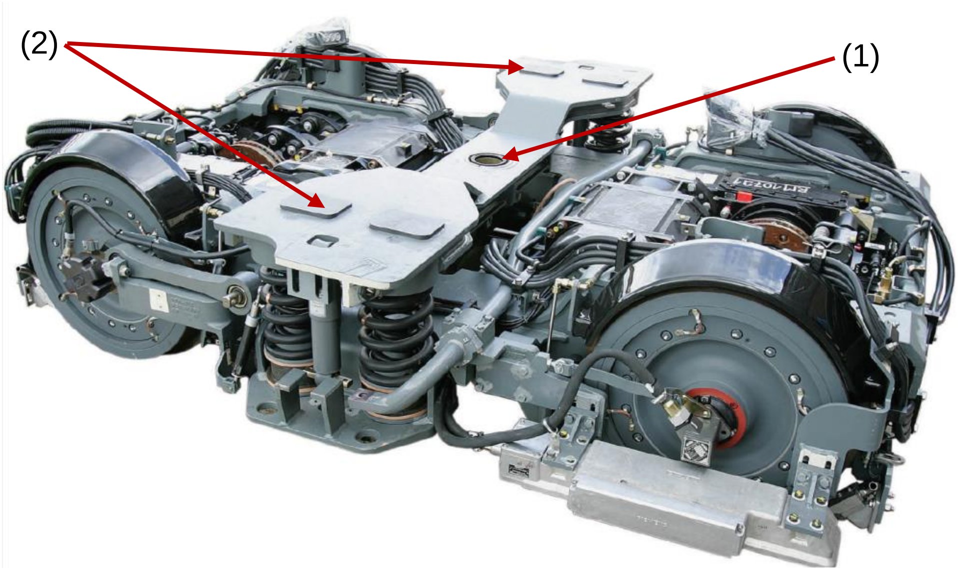


Figure 3-12: CL *300 bogie by* Alstom *with a yoke (1) and sliding plates (2) on the bolster [16, p. 9]*

The advantages of a rigid pivot are the simplicity of their design and low-cost manufacturing. This system allows lateral motions, therefore, have better dynamics in comparison with rigid joints. In addition, this with spherical joints can provide improved dynamic behavior for a traction bogie in comparison to other designs. [15, p. 104]

A disadvantages are the clearances in longitudinal and lateral directions this system has. Nevertheless, this design provides sufficient ride quality only for bogies having low lateral stiffness of the secondary suspension. [2, p. 62]

3.2.2 Traction rod

A traction rod is a steel bar linked at one end to the bogie frame and at the other end of the carbody frame (Figure 3-13). [2, p. 60]

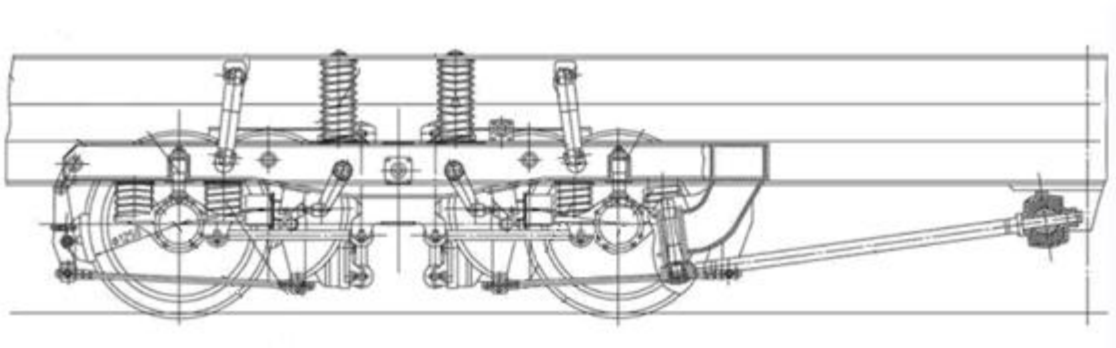


Figure 3-13: One traction rod linking the bogie and the carbody with rubber elements [15]

Traction rods are arranged with bushes and absorbing devices like rubber doughnuts at each end to improve comfort and minimize sharp forces as shown in the Figure 3-14. [15, p. 106]

Figure 3-14: Doughnuts at both extremes of the traction rod [2, p. 60]

Adding packed lead granules (approximately 0.5 million to 1 million) inside the hollow section of the traction rod reduces interior noise from rotational vibration transmitted from the propulsion system to the body via the traction rods by 2 dB to 5 dB. [17]

It is also possible to find configurations of bogies with two traction rods one in front and one behind as seen on the Figure 3-15.

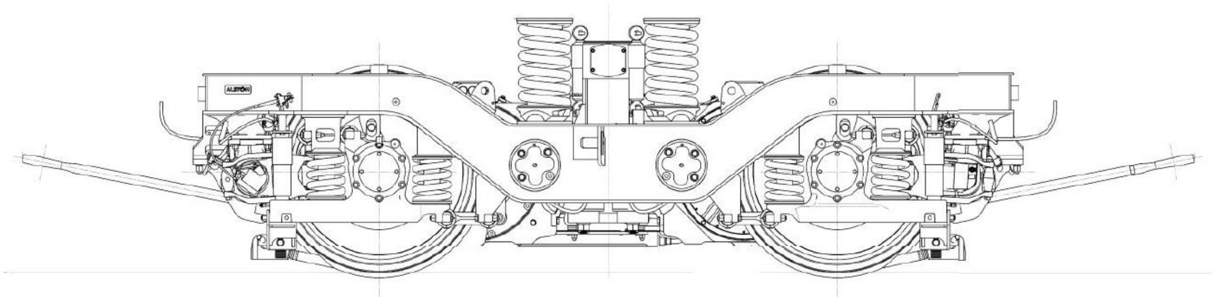


Figure 3-15: Two traction rods on the bogie CL 622 *by* Alstom *[16, p. 27]*

The principal advantage of traction rod connections against others like pivot is the wear-free. [7, p. 13]

3.2.3 Flat center plate

It is the most common connection for low speed and freight bogies. Consist of a plate in charge of transmitting the weight of the bogie and both lateral and longitudinal forces. It is normally located over the bolster, fitted in a crown bearing (Figure 3-16 and 3-17). A pin pivot on the center always secures the structure. The pin pivot has clearances on the yoke thus only provides emergency restraint. The center plate allows the bogie to rotate in curves and creates a friction torque that resists bogie rotation, therefore, the circular center plate provides a connection between the bogie and the car body in all directions. This arrangement to join the carbody and the bogie frame is the simplest and low cost. Logically it has disadvantages, the most significant is that the rotary movement occurs under a high contact pressure and, therefore, the surfaces are subject to significant wear. On modern designs, it is being used a flat central plate combined with elastic side supports that resist the rolling motion of the body and reduce the load on the central plate. [2, p. 61]

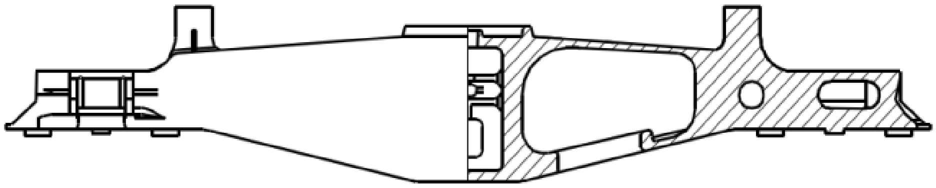


Figure 3-16: Section of a bolster with a flat center plate [2, p. 61]

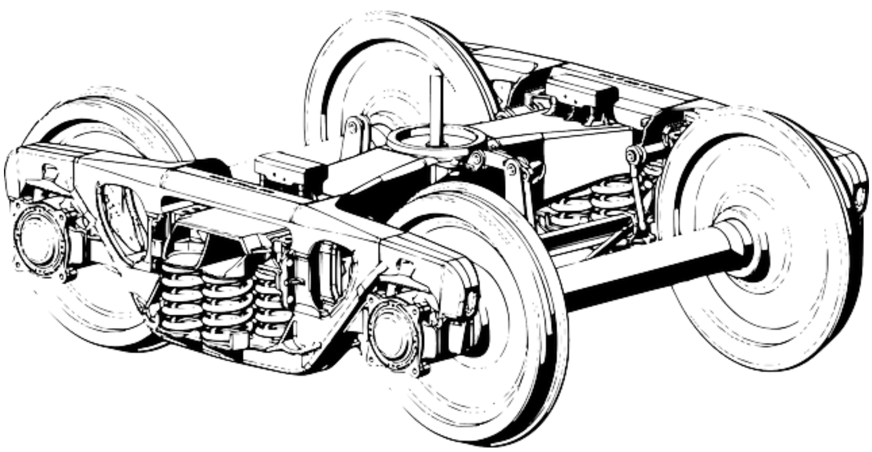


Figure 3-17: Three piece bogie with a flat center plate on the bolster [18]

3.2.4 Watts linkage

Watts linkage, also known as “Z link”, is a design that can be understood as an evolution of the pivot assemble since it consists of a central pivot and two others on both sides of it. These two on the sides join with the central one by a connecting rod (Figure 3-18). [19]

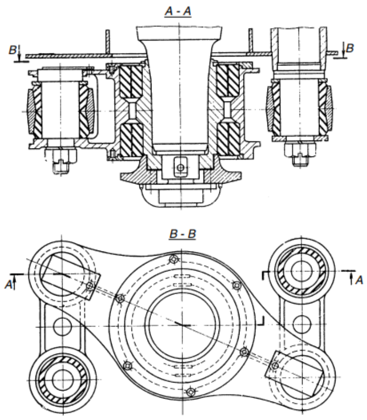


Figure 3-18: Watts linkage [2, p. 63]

This configuration allows the bogie to rotate and move laterally while longitudinal movement is guided by the geometry (Figure 3-19). In addition, the pivots in the linkage are provided with rubber washers and bushes to prevent the transmission of high-frequency vibrations through the mechanism and improve the driving comfort. [2, p. 62]

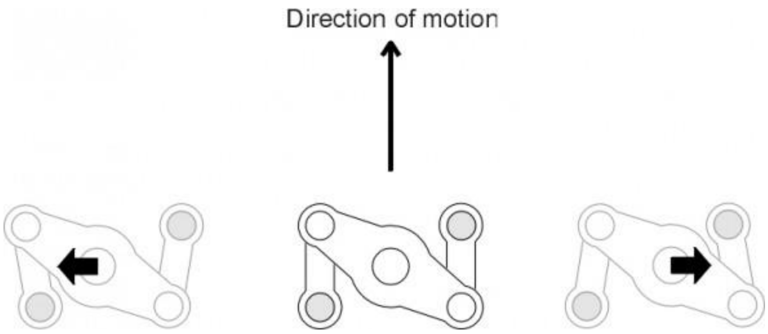


Figure 3-19: Motion of a watts linkage [20]

3.2.5 Bolsterless connection

A typical bogie design has a bolster joining transversely the springs of the secondary suspension from one side to the other of the bogie frame. In the middle of the bolster, there is the connection between the bogie and the carbody (Figure 3-12). In the bolsterless designs, this bolster is missed and the link between the bogie and the body rests only on the springs and a center pivot to transmit the forces. The bogie rotates under the carbody using the flexibility of secondary suspension. This requires that the suspension used allows both longitudinal and lateral movements for the correct turning of the bogie. Such requirement is solved with airsprings or flexi-coil springs explained below (subchapter

3.3.1 and 3.3.3 respectively). In such suspensions, the springs can achieve large longitudinal and lateral displacements to allow the bogie to rotate in curves (Figure 3-20). [2, p. 63]

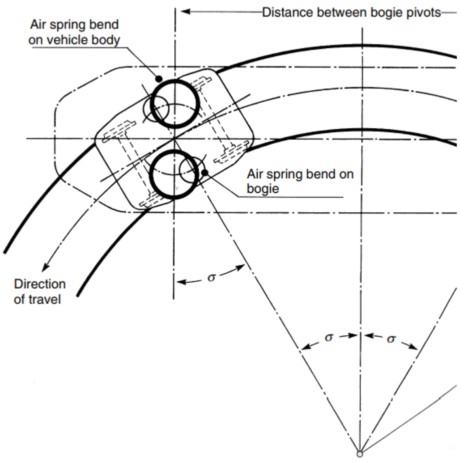


Figure 3-20: Deflection of the secondary suspension in a bolsterless connection [2, p. 64]

This design should use yaw dampers fitted longitudinally between the bogie and the carbody to assure stability in a straight line. [2, p. 66]

An advantage of this arrangement is the achieving weight reduction between 0.5 and 1.0t due to the saved bolster mass. [1, p. 53]

The Figure 3-21 shows an example of a bolsterless bogie which has a center pivot for the carbody connection and two airsprings in the secondary suspension.

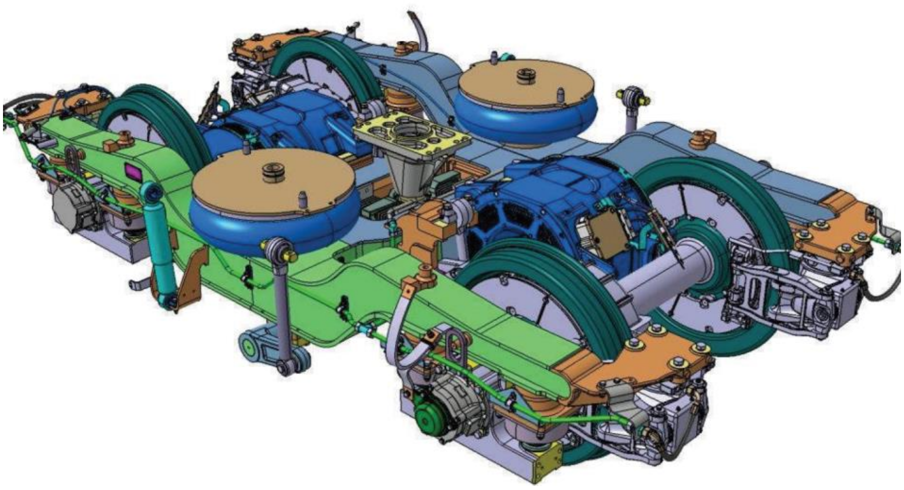


Figure 3-21: CL 606 by Alstom. Bolsterless, pivot combined with airsprings [16, p. 16]

3.3 Suspensions systems according to elastic element

The elastic element of a suspension, whether primary or secondary, can be composed of different materials. The combination of these materials and devices explained in this subchapter, makes a wide range of suspension possibilities. In this subchapter, a variety of devices that are currently in bogies with different applications, is explained. The Figure 3-22 shows a classification of these devices and materials.

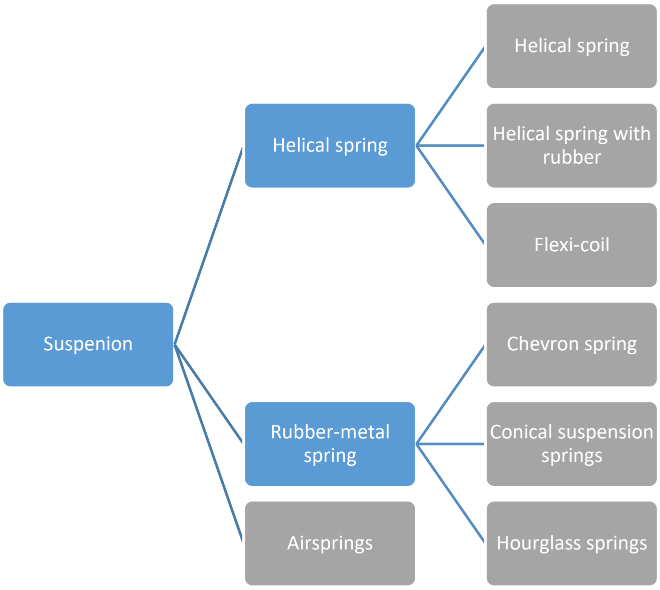


Figure 3-22: Elastic elements in suspensions

3.3.1 Airsprings

This is a modern device for vehicle suspension, typically adopted for the secondary suspension because it is more effective absorbing low-frequency oscillations [15, p. 97]. An airbag works using the compressibility of air, filling and emptying to modify the height of the train. The airspring itself is essentially a reinforced rubber laminate bellows (Figure 3-23).

Figure 3-23: Airspring [21]

The system excels especially when there are torsional strain and large horizontal force solicitations. It also absorbs a portion of the vertical deflection. Airsprings can provide high ride comfort levels and provide isolation of structure-borne noise and vibration. A Drawback of this system is the increased complexity of the vehicle and the higher rate of compressed air consumption. However, airsprings can be mounted in serial with a rubber emergency spring. This ensures operation with maximum speed, even when the airspring is deflated. [7, p. 18]

The airsprings can be arranged with no bolster, as it is explained in the subchapter 3.2.5. Two dispositions more are possible, arranging the airsprings above or below the bolster, both solutions will be more detailed in the subchapter 3.7 where tilting systems are explained.

Figure 3-24: SF 5000 E TDG by Siemens. Two airsprings below the bolster [7, p. 54]

3.3.2 Helical springs

The helical steel springs are one of the simplest systems, also the most common, of suspension found on modern bogies. This spring may be present in both the primary and secondary suspensions. Very often, rubber elements are arranged inside the steel coils to improve the dynamic behavior, cushioning and give more rolling quality. An evolution of this is the Flexi-coil suspension, which is considered separately due to its differentiation and specific characteristics, explained in the next subchapter.

Another common system with rubber elements is adding washers, for example, Hyrtel washers (thick rubber discs on both sides of the spring), this ensures an acoustical isolation between the bogie frame and the carbody (Figure 3-25). It is possible to combine this solution with others related with rubber, like mounting elastomeric springs in parallel to the steel coils, this provides a progressive suspension characteristic. This solution is used in the German train *VT612 DMU*. [22, p. 215]

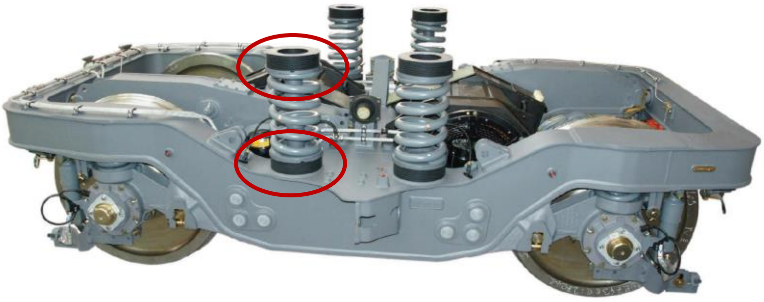


Figure 3-25: CL 494 by Alstom. Rubber washers on the extremes of the springs [16, p. 28]

Helical steel springs with low swiveling resistance fitted across the longitudinal axis of the vehicle prevent the introduction of torsional forces on the bogie frame. [7, pp. 8,12]

3.3.3 Flexi-coil

Flexi-coil springs are commonly used in the secondary suspension stage. The springs in a flexi-coil suspension are made of steel, a spherical rubber dome protrudes from above and below from each spring and absorb some of the horizontal forces. These domes are connected firmly to the carbody and the bogie frame. [23, p. 422] This system let lateral and longitudinal displacement thanks to the flexibility of the rubber domes (Figure 3-26). The stiffness is influenced by the number of coils, height, mean diameter of coils, wire diameter etc. The vertical forces are absorbed entirely by the steel springs. This type of suspension is most commonly used in modern rail passenger cars when air suspension is not required since it is cheaper to buy and to maintain than air suspension. [22, p. 284]

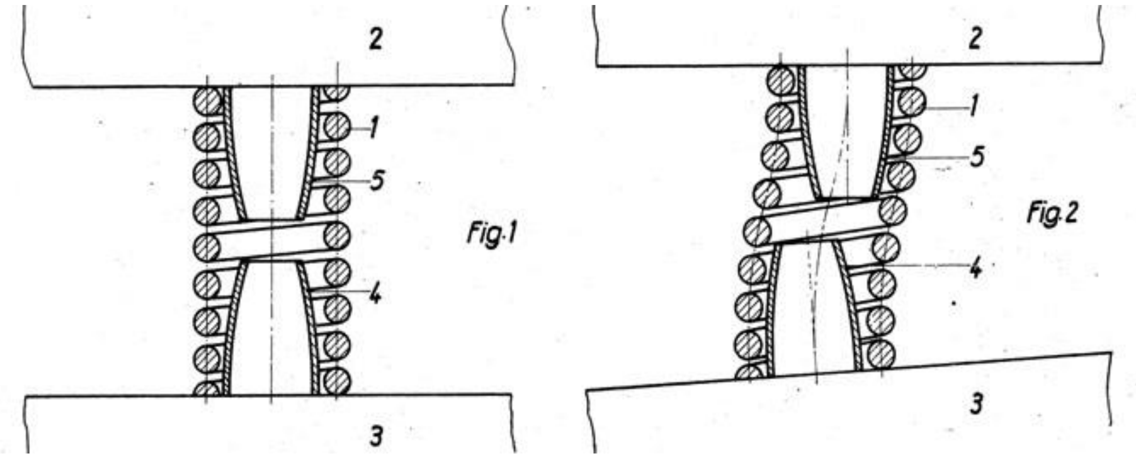


Figure 3-26: Eccentric displacement of the flexi-coil suspension [24]

An analysis from the University of Pardubice (Czech Republic) summarized in the article "The effect of spring pads in the secondary suspension of railway vehicles on bogie yaw resistance" concluded:

> "At a slow run in a curve, the bogie yaw resistance is low. However, the resistance is also low at the run of the vehicle in a straight track which can lead to worse riding stability characterized by a lower critical speed of the vehicle. In the case of a run in a curve at a high value of the cant deficiency, in which the need of a minimized bogie yaw resistance is the most important, the reduction of the bogie yaw resistance is not so significant, on the contrary." [25]

3.3.4 Rubber and rubber-metal springs

The elastomeric springs are suspensions made of rubber or composite materials that have an important natural hysteresis and are optimal to avoid high-frequency vibrations. The behavior of these materials varies according to their composition and its shape, presenting values of resilience, in general, higher than steel. [3, p. 16]

Figure 3-27: Xi´an by CRRC. Conical rubber-metal springs on primary suspension [26]

Conical rubber-metal springs provide an optimal filtration of vibrations in the axlebox, avoids fatigue problems by transmission of vibrations to the axle. Conical rubber-metal springs also provide three linear modes of flexibility, lateral, longitudinal and vertical. Modifying the geometry, different properties are reached [27, p. 274]. Therefore, this suspension is used to provide a bogie with the axle guidance capability.

The elastomeric materials of which these suspensions are composed have a natural tendency to flow or become unstable. They have a load memory produced by a change of properties permanent or semi-permanent by the result of applying continuous or undulatory loads. The temperature can produce changes in the height of the spring that, although being reversible, can produce changes of up to 12% variation with respect to the initial height with temperature variations of 30ºC. [3, p. 17]

This system is found both in primary and secondary suspension. A very common rubber-metal suspension system is the Chevron spring. Such system is a combination of elastomeric lays alternated with metal plates (Figure 3-28). Chevron springs provide lateral flexibility which improves the quality of the ride, especially on curves. Chevron springs applied on the primary suspension provides a lateral axle guidance widely used on metro bogies, more information about axle guidance in subchapter 3.8. [20] [7, p. 38]

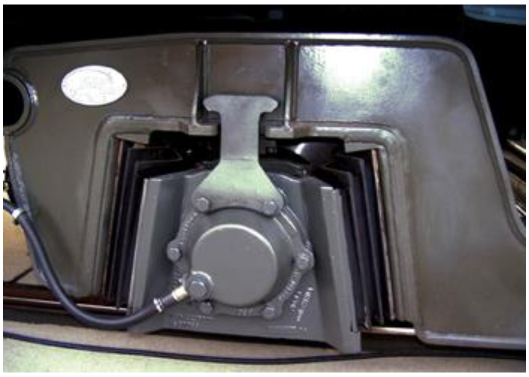


Figure 3-28: Chevron spring on primary suspension [3]

Lastly, there are elastomeric springs applied to the secondary suspension with an hourglass shape (Figure 3-29 and 3-51). These springs allow lateral and longitudinal displacement. In addition, rubber provides advantages such as their simplicity of manufacturing, low maintenance cost, less weight than steel and a long service life. This type of suspension offers a high load capacity and can store more elastic energy per unit volume than metals. [28, p. 271]

Figure 3-29: SF 30 Combino plus by Siemens. Hourglass springs on the secondary suspension

3.4 Classification of suspensions systems according to the geometry

The primary suspension should connect the axlebox to the bogie frame. This should be an elastic connection due to the axlebox must have a stroke. The different systems that allow this movement are classified in the Figure 3-30.

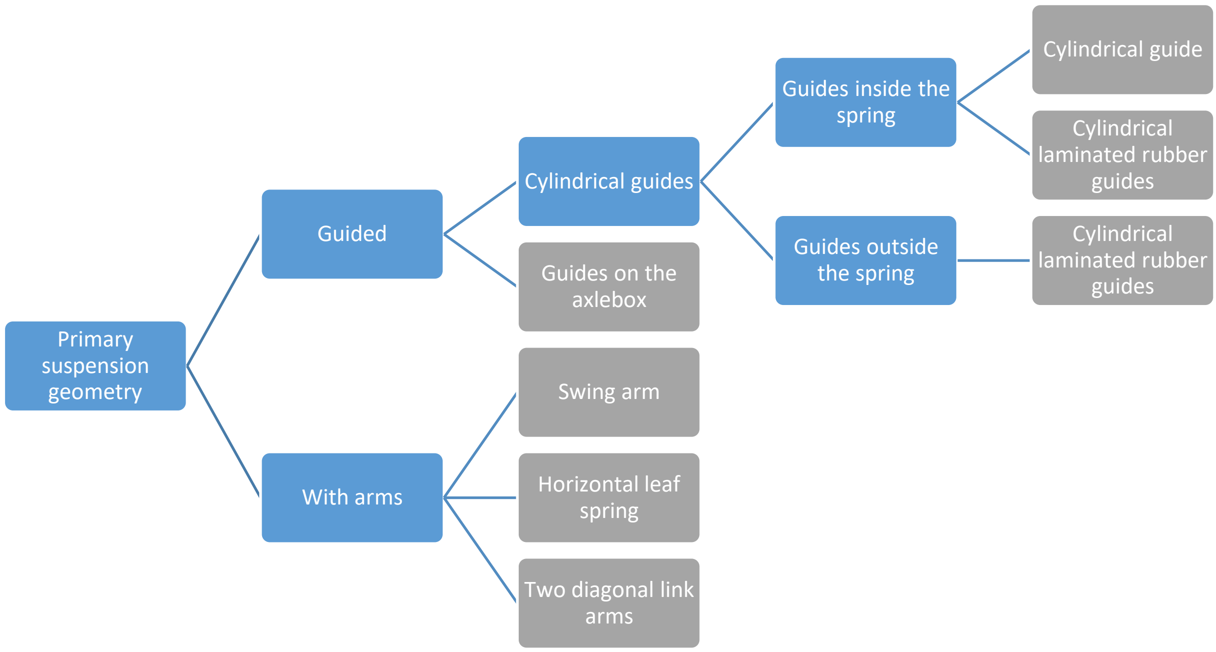


Figure 3-30: Arrangement of the primary suspension

3.4.1 Cylindrical guides inside the spring

This consists of a barrel inside the helical spring attached to the axlebox and a guide that slides inside of it attached to the bogie frame (Figure 3-31). The barrels are attached to the axlebox with rubber coaxial bushings, therefore, provides some flexibility between the wheelset and the bogie frame in the longitudinal and vertical directions. Due to the axial symmetry of the rubber bushes, the stiffness in longitudinal and vertical directions in the same. [2, p. 57]

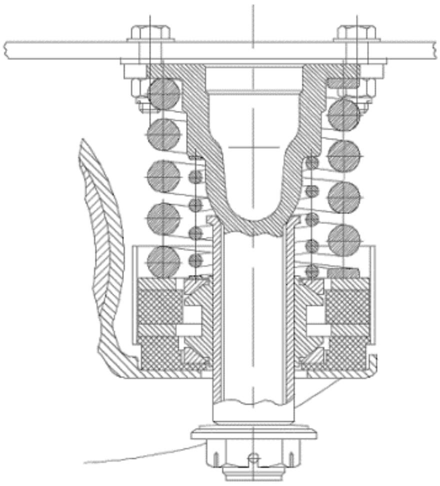


Figure 3-31: Cylindrical guide inside two concentric spring coils [2, p. 58]

3.4.2 Cylindrical laminated rubber guide inside the spring

Another system of guides are the ones with cylindrical laminated rubber achieved concentrically inside the helical spring (Figure 3-32). This arrangement allows lateral and longitudinal movement of the axlebox due to the flexibility of the rubber. This system is more compact than the system with the cylindrical rubber guides outside the spring (explained below). Due to the rubber guide should be inside the helical spring, this has a limited space, consequently, the transmitted forces are lower. [1, p. 56].

In comparison with the guides inside the spring mentioned above, the cylindrical laminated rubber guides get an excellent vibration isolation that provides more comfort on the train. [29]

This solution is widely used in the Japanese high-speed railways called Shinkansen. A bogie from this line who use this suspension is the *DT200.* [30, p. 52]

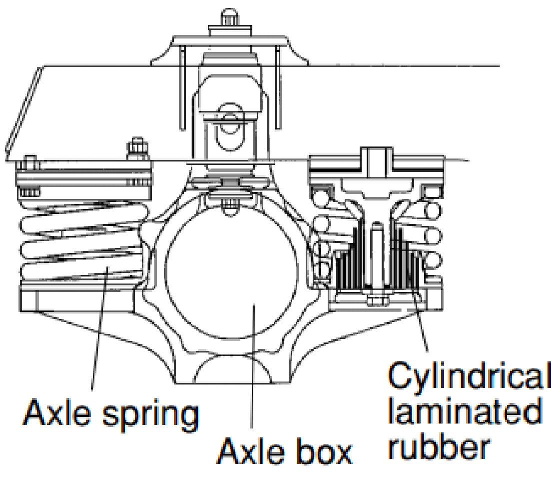


Figure 3-32: Cylindrical laminated rubber inside spring coils [2, p. 69]

3.4.3 Cylindrical laminated rubber guides outside the spring

This kind of axlebox guides design could be found on high-speed trains such as the French *TGV Y2-30*. Now the guide itself is outside the spring (Figure 3-33), the displacement of the axlebox along the guides occur by shear deformation of multi-layer rubber-metal block (Figure 3-34), and it is free from disadvantages. In order to obtain the optimum relationship of horizontal and vertical stiffness this block consists of two longitudinally oriented sections. This provides the bogie an excellent guidance on curves due the axlebox is free to move in yaw and adapt to the curve. [2, p. 58]

Figure 3-33: CL 511 by Alstom. cylindrical laminated rubber-metal guides outside the spring [16, p. 25]

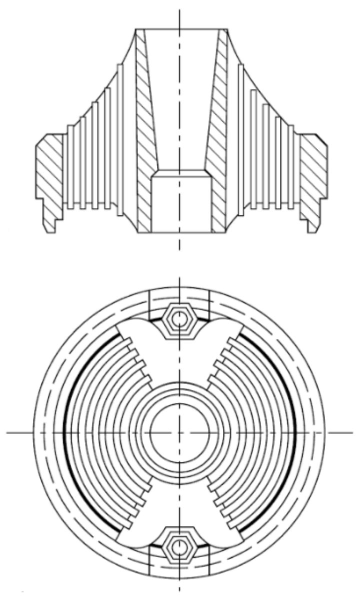


Figure 3-34: Section and elevation of a cylindrical rubber-metal guide [2, p. 58]

3.4.4 Swing arm

In this configuration, the axlebox has a rod hooked to the chassis by bearings. This allows a circular movement where the center of the circle is the point of union between the arm and the bogie frame. A spring, typically a helical steel coil, completes the structure (Figure 3-35).

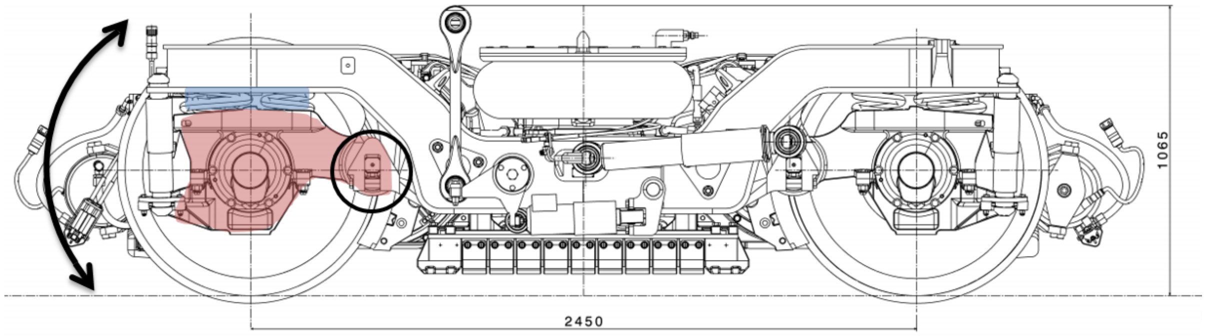


Figure 3-35: CL 506 by Alstom. Swing arm (red), helical springs (blue). Motion of a swing arm [16, p. 17]

The swing arm system has several functions including the support of the axlebox, connection of the bogie and axlebox, and also transfers brake and traction force in the longitudinal direction from the axle to the bogie. Elastic bearings can be arranged on the link between the bogie and the swing arm to provide lateral free movement. This allows the bogie axle guidance on curves. The system's vertical, longitudinal, and lateral stiffness can be adjusted according to design requirements and operating conditions to prevent derailment and ensure stable operation during high speed.

This configuration is found in metros and intercity trains, but also on high-speed trains like *CRH-1A* in *China*. [31]

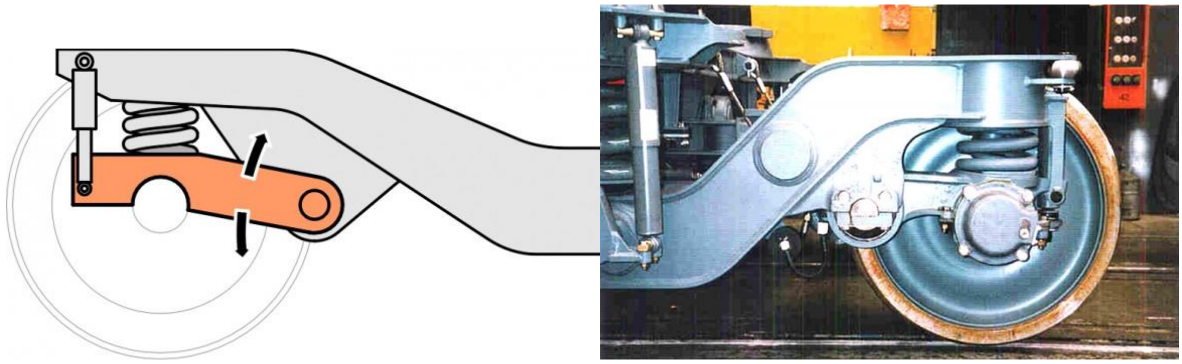


Figure 3-36: Draw/picture of a swing arm [20]

3.4.5 Horizontal leaf springs

In this configuration, a horizontal leaf spring connects the axlebox and the bogie. The idea is very similar as the swing arm system, but instead of a rod (Figure 3-36) there is a plane horizontal leaf which is linked also to the axlebox, it is not a part of it (Figure 3-37). The connection of the steel leaf in both extremes is made by rubber elements allowing yaw movement of the leaf and consequently, lateral movement of the axlebox. It is another system to provide axle guidance to the bogie. [32, p. 37]

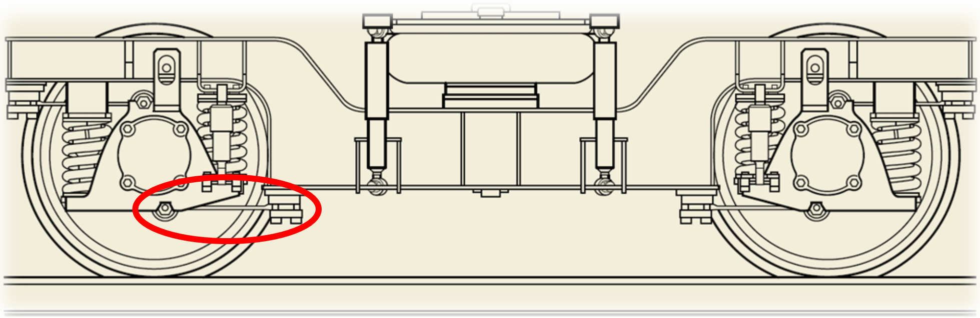


Figure 3-37: Horizontal leaf spring [32, p. 37]

Two parallel horizontal leaf springs instead of one is also a possibility to guide the axlebox (Figure 3-38). Again, the extremes of the two pairs of leaves are connected by rubber bushings. This arrangement is used in the *MD-522* by *Bombardier* which is used in the ICE (German High-speed trains) trailer bogies (Figure 3-39). [32, p. 36]

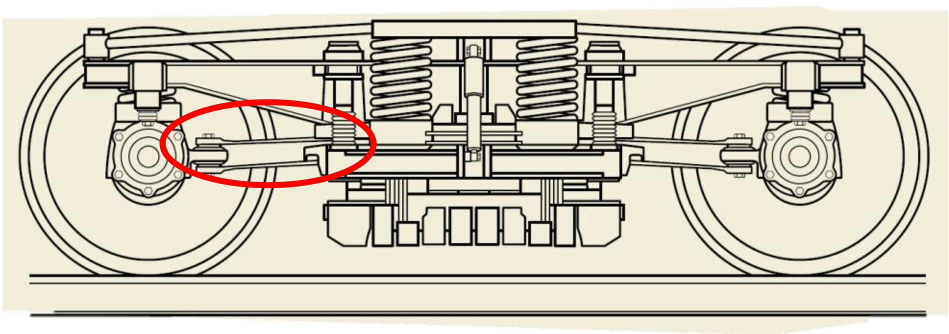


Figure 3-38: Two parallel leaf springs [32, p. 36]

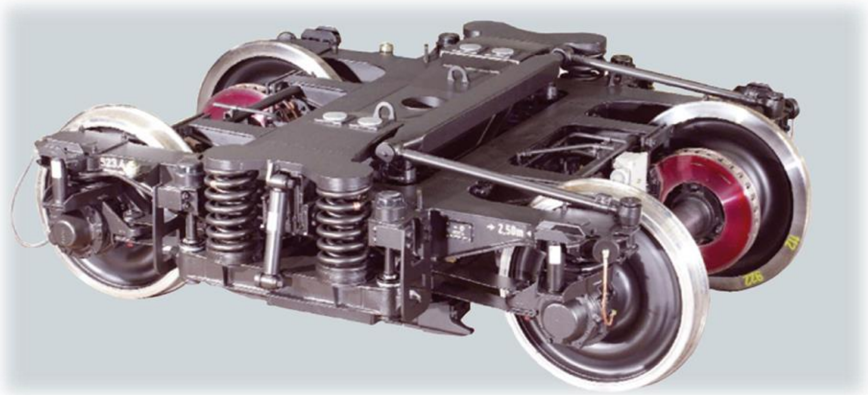


Figure 3-39: ICE bogie MD-522 by Bombardier. Uses two parallel leaf springs [33]

3.4.6 Two diagonal link arms

This system consists of two arms connected from one side to the axlebox and the other the bogie frame, arranged in a diagonal position (Figure 3-40). All the connections are done by rubber elements or elastic bearings to let flexibility enough and avoid friction surfaces. The main problem is obtaining linear motion of the axlebox when the arms rotate. The problem can be solved increasing the longitude of the arms, but this is committed to space. [2, p. 59]

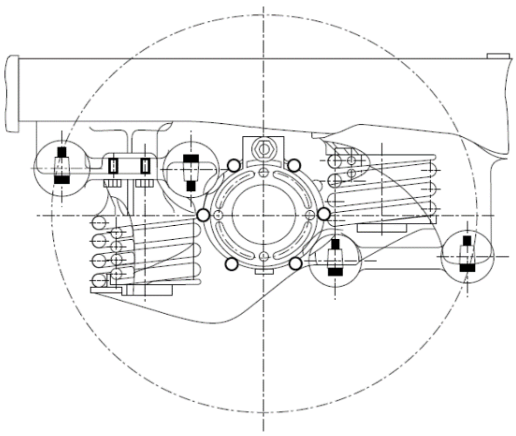


Figure 3-40: Scheme of two diagonal link arms [2, p. 59]

This configuration is widely used by *Alstom* for example in the *CL 624* showed in the Figure 3-41

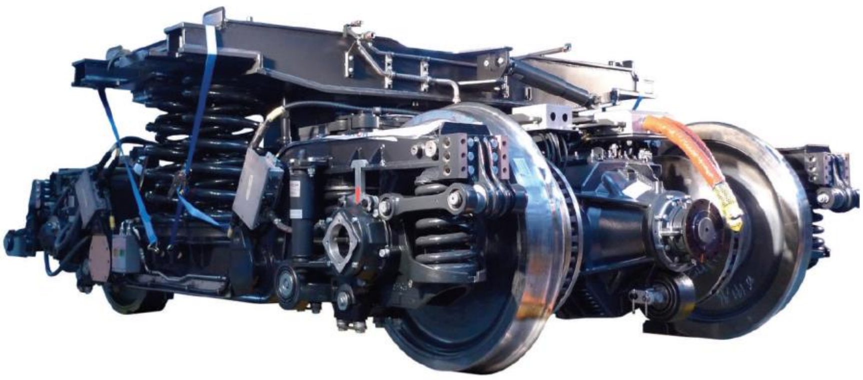


Figure 3-41: CL 624 by Alstom. Uses two diagonal link arms on primary suspension [16, p. 23]

3.4.7 Horn liner guides

On this configuration, the axlebox is linked to the chassis through guides in the own frame of the bogie allowing a vertical movement. This system is also known as *horns* and is the simplest way to arrange the axlebox (Figure 3-42). Transmits more vibrations than other systems due there are no intermediate elements between the axle and the bogie frame as there are in the swing arm system for example. It is more compact but very limited in terms of movements refers, only allows vertical movement. It is used for its simplicity and low cost. [20]

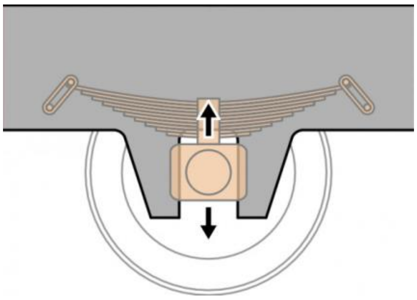


Figure 3-42: Axlebox supported by horns and leaf spring [20]

The main disadvantage of this layout stands the hard pressure of the axlebox against the horn during the braking or the acceleration. Therefore, a high rate of wear on the sliding surfaces occur prematurely, moreover, stresses on the base of the horn are created accelerating the creation of cracks (Figure 3-43). [20]

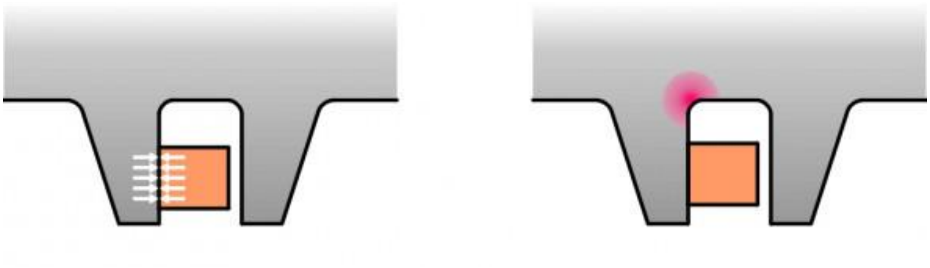


Figure 3-43: Friction (left) and stress (right) caused by braking and longitudinal forces [20]

3.4.8 Cylindrical stubs

This is an evolution of the system explained above *Horn liner guides*. The axlebox slides up and down guided by two stubs bolted to the bogie frame (Figure 3-44). Has the same disadvantage as the Horn system but with the friction surface is reduced, therefore there is less wear. [20]

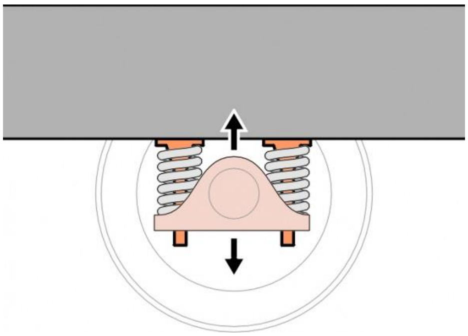


Figure 3-44: Axlebox guided by cylindrical stubs [20]

3.5 Dampers

The function of the damping elements is to absorb the oscillations produced by the elastic suspension elements in the shortest possible time. Dampers absorb the kinetic energy that is transmitted to the suspended mass and reduce the time in which the wheel-rail adhesion varies due to the oscillations produced by the elastic elements. They also break the oscillations produced in the suspended mass and in the non-suspended mass. [3, p. 20]

Dampers aim to provide the necessary comfort to the passengers of the vehicle and limit the carbody movements.

Dampers can be classified into two groups: friction dampers and hydraulic dampers.

3.5.1 Friction dampers

Are the simplest ones but widely used on freight vehicle or on bogies where the comfort is not essential (Figure 3-45). [2, p. 53]

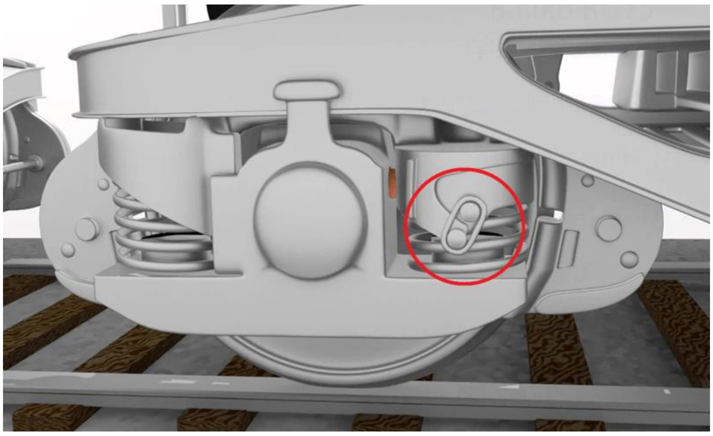


Figure 3-45: Friction damper in parallel with two spring coils [34]

Principal problem is that the damper starts working when the friction force is exceeded, so the vehicle starts from an initial situation of blocked suspension. Once the friction force is overcome, the damping force decreases with the speed instead of increasing with it. In addition, continuous maintenance is necessary due to the wear and tear suffered. [3, p. 21] [35, p. 23]

3.5.2 Hydraulic dampers

Those are the ones that use the viscosity of a fluid or the compressibility of a gas to absorb the kinetic energy. There are basically two different hydraulic dampers, monotube and double tube shock absorbers being the second the most common for their best behavior. Hydraulic dampers are the most common shock absorbers used on passenger bogies. Those can be used in both primary and secondary suspension. [2, p. 55] Dampers arranged in parallel to the primary suspension system ensure an optimal vibration and sound decoupling. This solution is extended used in Siemens bogies for passengers like the SF 200. [7, p. 14]

Hydraulic dampers are also used to dampen the yaw (Figure 3-46) and the tilting, also the axle guidance (lateral movement) if the bogie is provided with it.

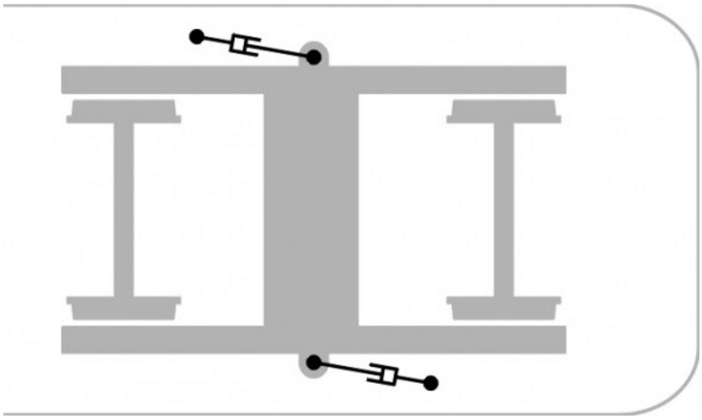


Figure 3-46: Plant of a bogie with yaw dampers [20]

The correct usage of dampers is relevant to obtain a good comfort in the carbody, that's why many arrangements are available on the market in the sense of getting specific properties according to demand. For example, the SF 600 made by Siemens, which is defined as a high-comfort bogie for passengers train, has a yaw damper system fitted with hydraulic dampers, which can be automatically activated depending on the vehicle speed to improve the stability of the carbody. [7, p. 45].

Nevertheless, using an active stabilization of the wheelsets negates the need for yaw dampers between bogie and carbody, which, in the case of conventional bogies are required to stabilize the sinusoidal movement of the bogie. Furthermore, lower weight designs are possible due to potential elimination of intervehicle dampers, that means less material required. This is applied on the *FLEXX Tronic ARS* from *Bombardier*. [36]

3.6 Bogie frame shape

The bogie frame is the bogie chassis, where all the components are linked. There is not a specific design or shape; it changes depending on the demands of each usage. It is made, in most designs, of high strength steel, connecting each part by welding. Each part can be made of steel sheets, forged or cast pieces. [37]

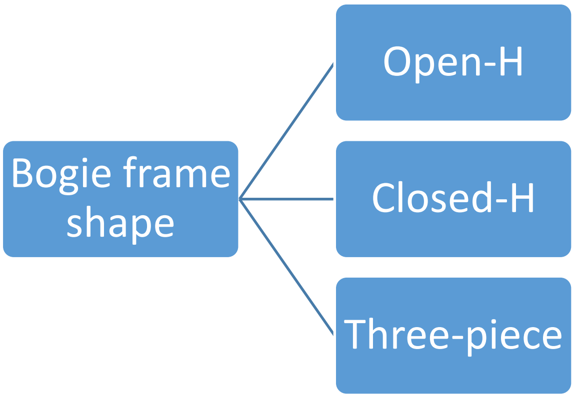


Figure 3-47: Bogie frame classification

3.6.1 Open H-frame

The most common design is the open H-frame (Figure 3-48). It is a light design widely used in high-speed trains like the *ICE 3 – DB, AVE S103 – RENFE, Velaro RUS – Russia*. All these trains use the First-Class Siemens SF 500 bogie, which is robotically welded [7, p. 45]. This frame shape is commonly combined with a swing arm with helical springs as the elastic element as shown in the Figure 3-36 from the subchapter 3.4.4.

Figure 3-48: Open H-frame [38]

The bearings can be located inboard with the bogie frame lying between the wheels as shown in the lower image of the Figure 3-49, or outboard, keeping the wheels in the inner part, top image of the Figure 3-49. Inboard bearings make the frame lighter and more compact. This last configuration is used on regional passenger trains and trams whose modest travel speed is unlikely to result in bearing failure. [20]

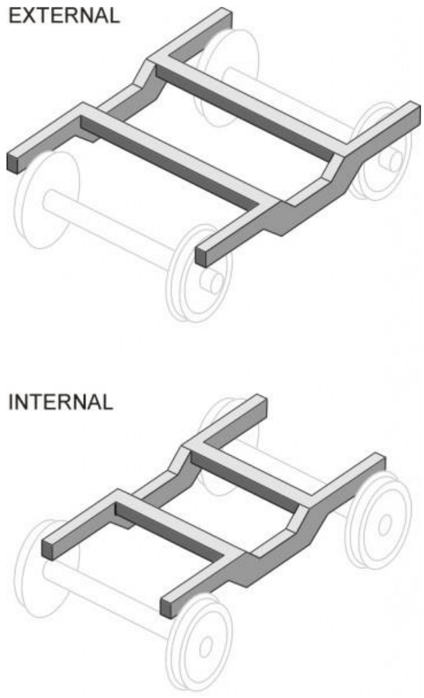


Figure 3-49: External and internal arrangement of the wheels on the bogie frame [20]

3.6.2 Closed H-frame

There exist also a closed H-frame that links the extremes of the *H* with a bolster (Figure 3-50). This provides more torsional resistance, consequently, it has a higher weight. This bogie frame is found on locomotives like the *CL 622* from *Alstom* [16, p. 27]. However, it is also rarely found on bogies for high-speed trains like the *SF 500 DSW* from *Siemens*. [7, p. 46]

A well-known railway manufacturing company as Siemens, inform that their bogie frame on the *Vectron* is welded almost entirely with the use of robots, and does not incorporate any castings or forged parts because of their bad mechanical properties. [8]

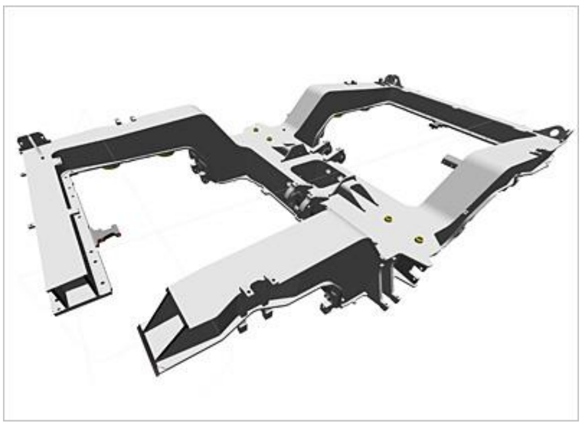


Figure 3-50: Closed H-frame from Siemens Vectron [8]

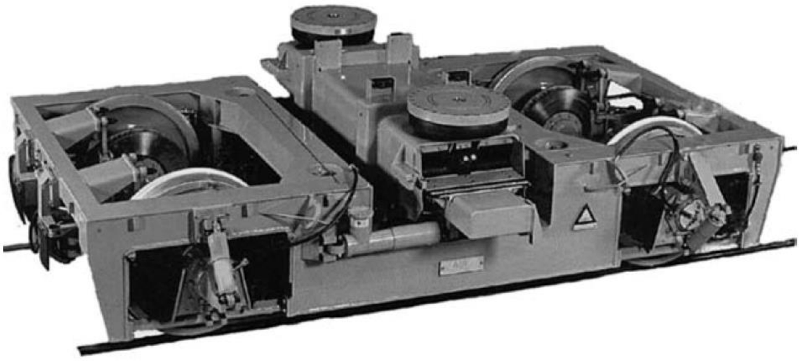


Figure 3-51: X-2000 by Bombardier. Closed H-frame and chevron springs [2, p. 69]

3.6.3 Three-piece frame

This type of chassis consists, as the name suggests, of three pieces, two side frames linked to the central bolster by the secondary suspension as shown on the Figure 3-52. The connection from the bolster to the car body is via a central pivot and side bearers with sliding surfaces. There is no primary suspension between the wheels and the side frames in the most of these bogies. The three-piece bogie is not common in Western Europe, is widely used in North America, Australia, Africa and Russia and a modern version is currently being introduced into Great Britain [39]. Three-piece bogie frames are widely used on freight bogies due to their low cost, inherent simplicity and ability to articulate in poor track conditions. [40, p. 366]

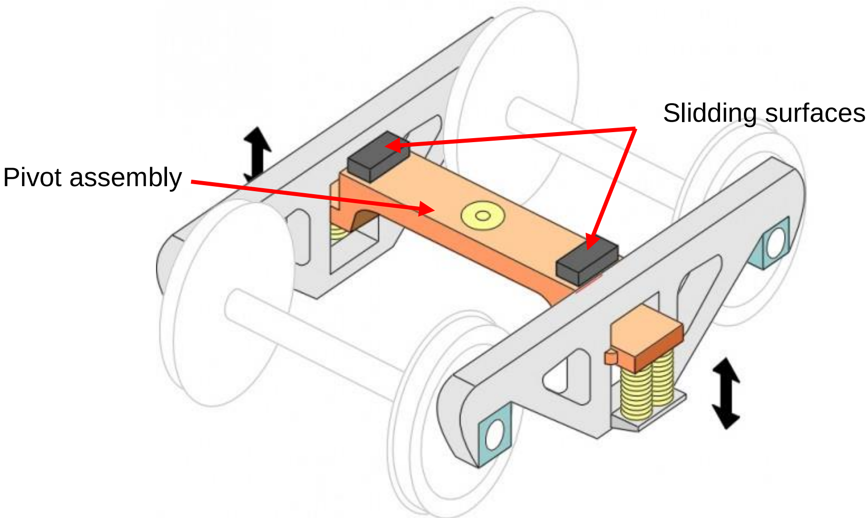


Figure 3-52: Draw of a three-piece bogie frame [20]

3.7 Tilting

The tilting trains arise from the need to reduce the centrifugal forces in curves at high speed. This force pushes the passenger toward outside of the curve, hence comfort is reduced. To solve this problem, some trains are equipped with a hydraulic or electric system that makes the carbody tilt to the side where the center of the curve is (Figure 3-53). [1, p. 59]

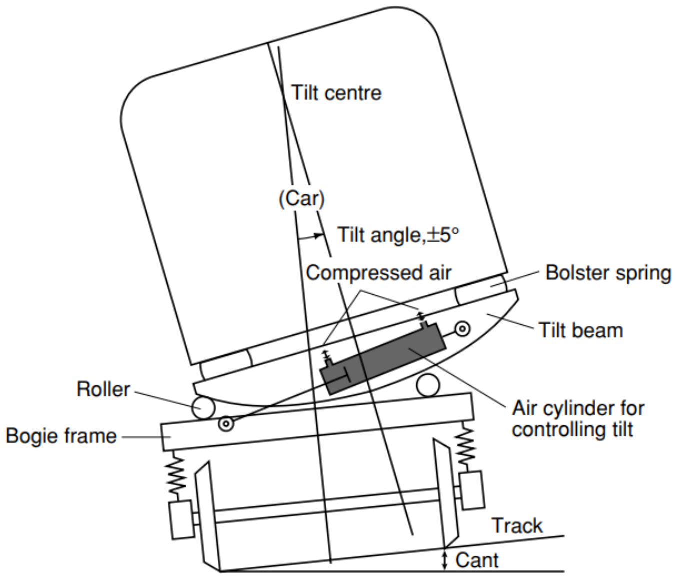


Figure 3-53: Section of an active tilting bogie with secondary suspension above the bolster [1, p. 59]

A tilting system simulates a cant effect in railways which do not have, thus a train can drive through places where initially were not designed for high-speed. Even if the railway track is equipped with a cant, may not enough for a high-speed train to run on it, hence the inclination helps to improve comfort and drive faster. [2, p. 197]

An example of a bogie that uses a tilting system, is the *CL 624* produced by *Alstom* and used by *RENFE* or *Trenitalia*. This bogie is used in high-speed trains with an operation speed around 225-250 km/h. The manufacturer *Alstom* specifies that "has an active hydraulic tilting system (+/- 8º) to enable to do high-speed curves on conventional lines". [16, p. 23]

There are four ways to tilt the carbody; two with no bolster, one just elevates the secondary suspension and let the carbody naturally swings outwards the curve. The other way is to actuate directly to the secondary suspension to make it tilt, for example, applying differential control to the air springs. The other two systems that use a bolster are the most complicated but also most effective tilting systems. They are differentiated because one has the bolster above the secondary suspension and the other below, this last avoids the increasing of the curving forces, and this is probably the most common of all schemes (Figure 3-53). These two last are active ways to tilt in the sense on there are arranged actuators (hydraulics or electrics) that force the car body to tilt. [2, p. 333]

Tilting systems for high-speed trains is widely used due to their comfort gain. In Japan for example, a passive system is used, in Italy, *Pendolino* trains have an active control system, in Spain a completely different passive system had been developed for the *Talgo*, however, in France and Germany, the high-speed lines are being built on new alignments that don't justify the expense and complication of tilt technology. [20]

The Figure 3-54 summarizes the classification of Tilting systems.

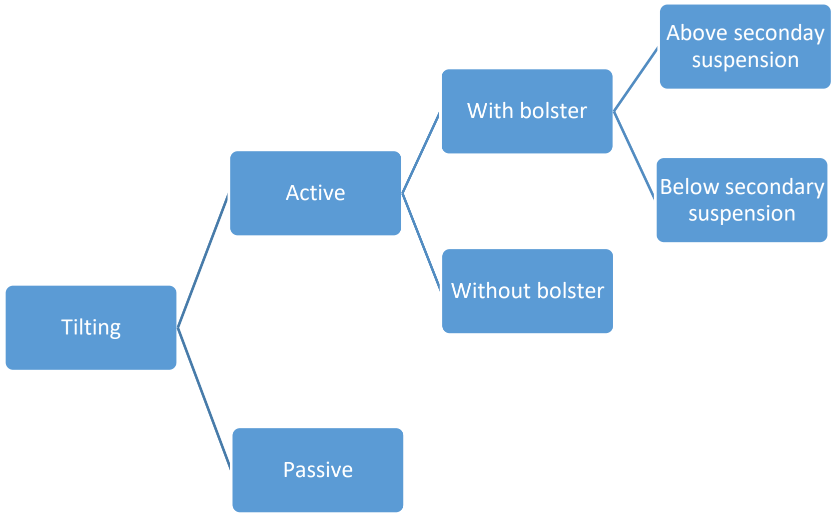


Figure 3-54: Tilting systems

3.8 Axle guidance

The steering is the capacity that the bogies have on the wheelset to adopt a radial position in curves (Figure 3-55). This brings a significant decrease of flange wear (10-time wear reduction [36]) and lower track forces that will prolong the life of the track and postpone the need for rail replacement. It provides a better behavior on sharp curves, on a tram railway for example [20] [41, p. 62]. Finally, the curve squeal noise is eliminated or partially eliminated. [36]

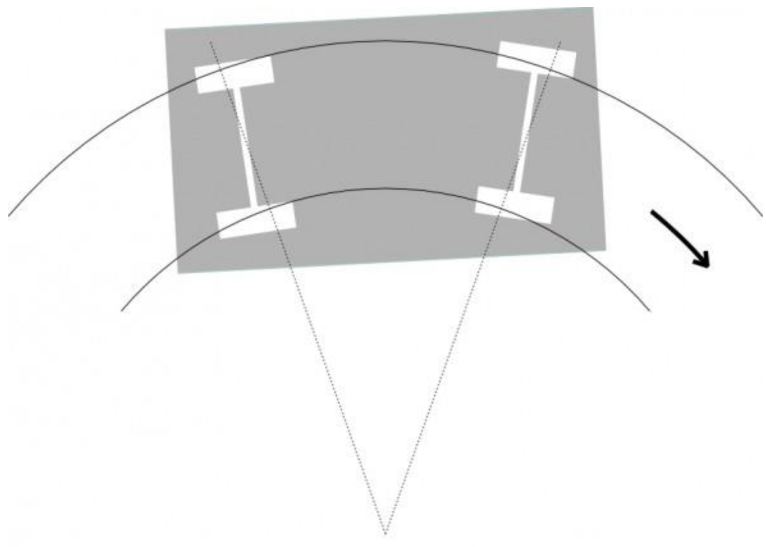


Figure 3-55: Partial radial position of the wheelset [20]

There are three different ways to get steering of the wheelset. The first is the one that gets the yaw of the wheelset through the interaction between the rail and the wheel. The second system, the yaw angles of the wheelsets are determined by the angle of the bogie relative to the vehicle body, the wheelsets are forced to get radial position due to the linkages between the wheelset and the vehicle body. [2, p. 79] This second system has been used successfully on the Japanese *Railways Hokkaido Series 283* passenger diesel motor units, where tests have shown that it reduces lateral forces on the rail by a half or more. The last system integrates sensors and actuators, either hydraulic or electric, that force the axlebox to adopt radial position. This is the most complicated system, but also the most effective (Figure 3-58) [20]. The two first systems are passive ways of self-steering due there is any actuator that controls the yaw of the wheelset.

Yaw dampers can be arranged to improve the smoothness of the steering and avoid wheelset hunting (Figure 3-56). [1, p. 54]

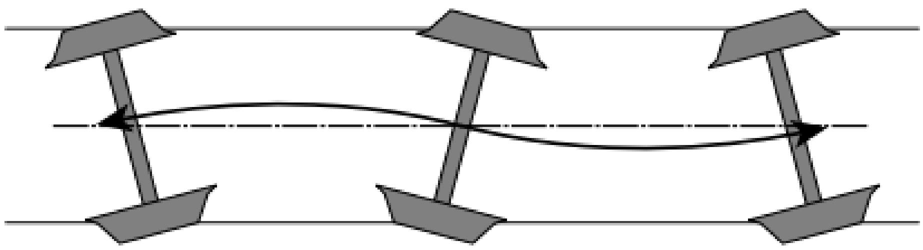


Figure 3-56: Wheelset hunting [1, p. 54]

To summarize, wheelset steering can be classified into the following three groups:

- Wheelsets yawed by the wheel-rail contact forces.
- Wheelsets yawed by the relative rotation between the bogie frame and vehicle body.
- Wheelsets yawed by an external energy source (electric, hydraulic, or pneumatic actuators).

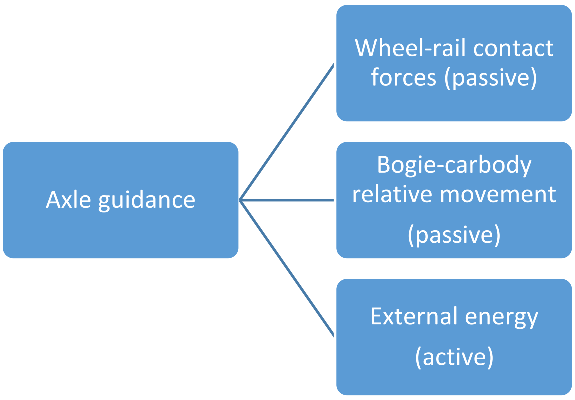


Figure 3-57: Axle guidance systems

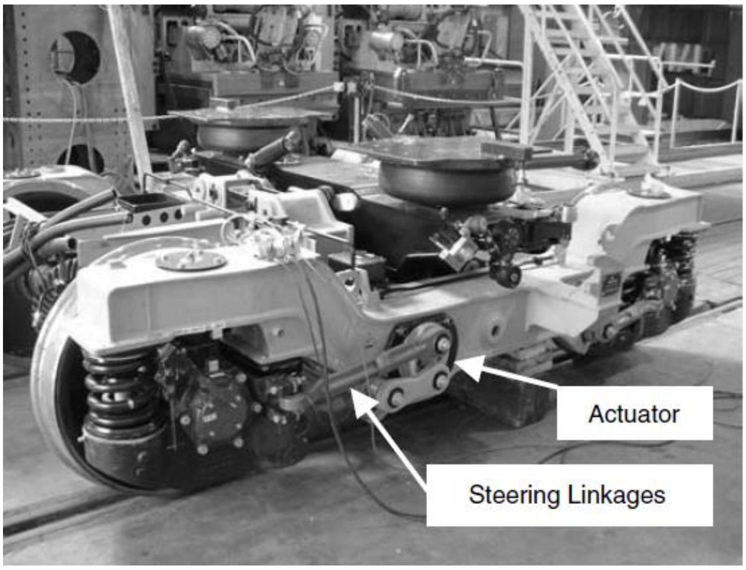


Figure 3-58: Active control of the axle guidance [2, p. 345]

To understand how the axle can have yaw freedom to adopt radial position, the Figure 3-59 explains four different systems [2, p. 348]. The axlebox yaw must be compatible with the primary suspension, which is joining the axlebox to the bogie frame, hence the suspension must provide freedom in lateral and longitudinal directions. This is not achieved by all the suspensions schemes explained in suspensions chapters. To provide a bogie with axle guidance, the selected suspension system should allow the lateral and longitudinal displacement mentioned above.

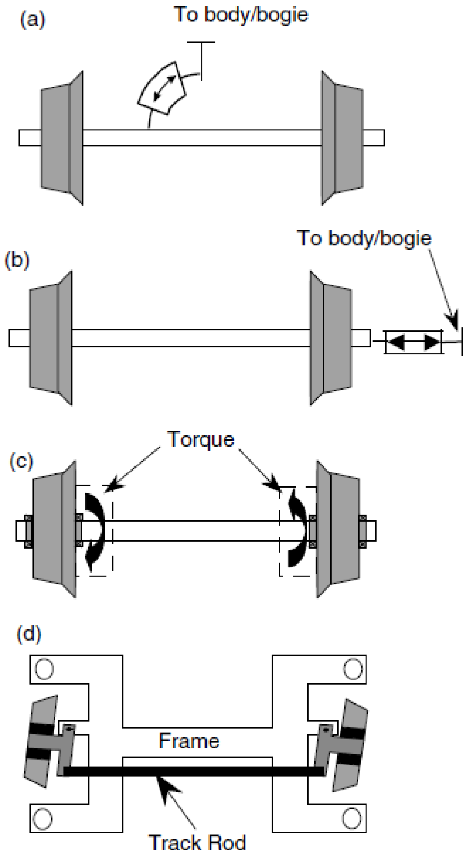


Figure 3-59: Configurations to adopt radial position of the wheelset [2, p. 348]

To relate these concepts, both how the mechanism is arranged and its disposition, the *X2000* by *Bombardier* is a good example (Figure 3-58). It has chevron springs on the primary suspension that allows the lateral movement of the axes and it doesn't have any mechanism that forces the radial position, so it is a passive system. Therefore, it is *Wheelsets yawed by the wheel-rail contact forces* and belongs to the case *(b)* in the Figure 3-59. This arrangement is more frequent on metros and trams due to the good radius of curvature but also in some locomotives like the *X2000* of this example.

The technology by *Bombardier* named *FLEXX Tronic* used in high-speed bogies, has a novel and pioneering axle guidance system that is not seen in any other design on the market. Has an active system through actuators and sensors that achieve a yaw movement of the shaft, so it corresponds to the *(a)* image of the Figure 3-59. More information on the link. [36]

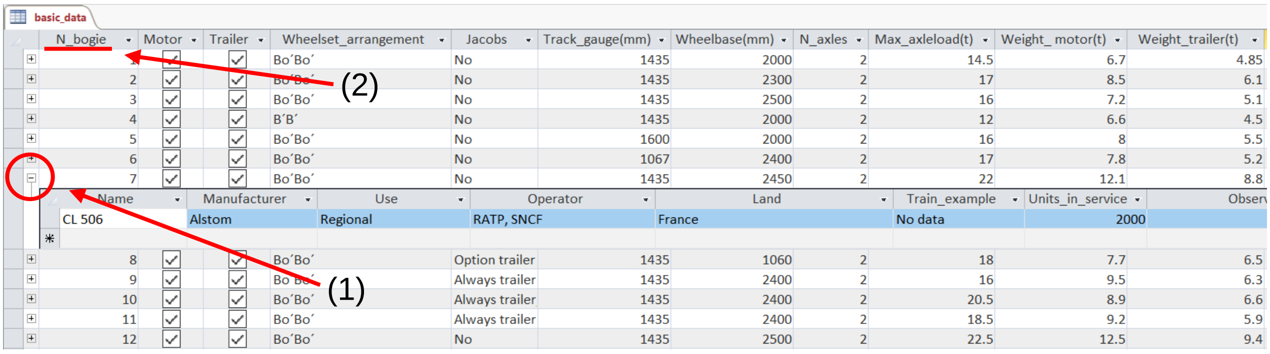
4 Creation of Database

4.1 Introduction

All the possible configurations detailed in the previous chapter must be grouped and compacted in order to extract results quickly and easily. The creation of a database is a methodical way to achieve it. A database can store the technical specifications of the bogies with the same pattern and thus be able to compare two bogies of different manufacturers, which express the information in different ways. Otherwise, this presents a problem; not all manufacturers give the same information, for example, in the technical sheet of a bogie can be explained how the carbody connection is done, but another technical sheet cannot be mentioned. Therefore, the database here has a comparison problem. However, the database is ready to be filled with the missing information at any time. Thus, the database is active and modifiable.

4.2 General characteristics

The information is saved through tables connected to each other to relate the information about a record in different tables. The Figure 4-1 shows how are the tables related using a drop-down box that let the user know which bogie is being consulted.


basic_data

N_bogie	Motor	Trailer	Wheelset_arrangement	Jacobs	Track_gauge(mm)	Wheelbase(mm)	N_axles	Max_axleload(t)	Weight_ motor(t)	Weight_trailer(t)
1	✓	✓	Bo´Bo´	No	1435	2000	2	14.5	6.7	4.85
2	✓	✓	Bo´Bo´	No	1435	2300	2	17	8.5	6.1
3	✓	✓	Bo´Bo´	No	1435	2500	2	16	7.2	5.1
4	✓	✓	B´B´	No	1435	2000	2	12	6.6	4.5
5	✓	✓	Bo´Bo´	No	1600	2000	2	16	8	5.5
6	✓	✓	Bo´Bo´	No	1067	2400	2	17	7.8	5.2
7	✓	✓	Bo´Bo´	No	1435	2450	2	22	12.1	8.8
8	✓	✓	Bo´Bo´	Option trailer	1435	1060	2	18	7.7	6.5
9	✓	✓	Bo´Bo´	Always trailer	1435	2400	2	16	9.5	6.3
10	✓	✓	Bo´Bo´	Always trailer	1435	2400	2	20.5	8.9	6.6
11	✓	✓	Bo´Bo´	Always trailer	1435	2400	2	18.5	9.2	5.9
12	✓	✓	Bo´Bo´	No	1435	2500	2	22.5	12.5	9.4

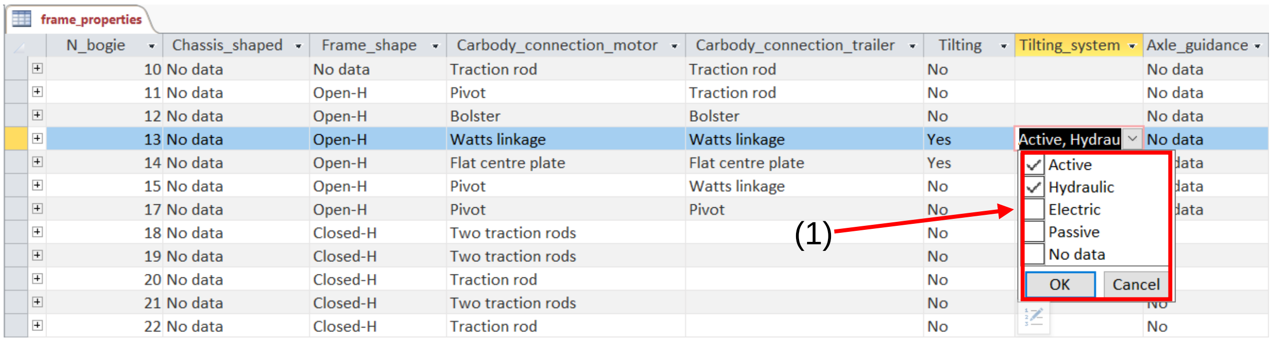
Name	Manufacturer	Use	Operator	Land	Train_example	Units_in_service	Observ
CL 506	Alstom	Regional	RATP, SNCF	France	No data	2000	

Figure 4-1: Relation between tables through the drop-down box (1). N_bogie field (2)

All the tables have a common field called *N_bogie* (see the Figure 4-1). This field numbers each bogie in order that has been added to the database. It is the tool to identify a bogie through all the tables. Naturally, *N_bogie* remains in all the tables, moreover, is always in the first position.

There is another common field in all the tables called *Observations*. In this field, all the extra information that a manufacturer gives about a bogie is saved. It is also used for the information that has no place in other fields. *Observations* is always in the last position in all the tables.

There are some fields where the stored information is not free to be filled, to facilitate the filling, there is a lookup wizard with default options. The options of this lookup wizard can be extended as new designs and options appear in the market (Figure 4-2).


frame_properties

N_bogie	Chassis_shaped	Frame_shape	Carbody_connection_motor	Carbody_connection_trailer	Tilting	Tilting_system	Axle_guidance
10	No data	No data	Traction rod	Traction rod	No		No data
11	No data	Open-H	Pivot	Traction rod	No		No data
12	No data	Open-H	Bolster	Bolster	No		No data
13	No data	Open-H	Watts linkage	Watts linkage	Yes	Active, Hydrau	No data
14	No data	Open-H	Flat centre plate	Flat centre plate	Yes		data
15	No data	Open-H	Pivot	Watts linkage	No		data
17	No data	Open-H	Pivot	Pivot	No		data
18	No data	Closed-H	Two traction rods		No		
19	No data	Closed-H	Two traction rods		No		
20	No data	Closed-H	Traction rod		No		
21	No data	Closed-H	Two traction rods		No		No
22	No data	Closed-H	Traction rod		No		No

Figure 4-2: Fragment of frame_properties table Lookup wizard (1) to choose tilting_system field

In the technical sheets provided by manufacturers, there are not always all the information that the database can store, in those cases, the field which there is no information about will be filled with *No data*. However, the field can be filled in future if the data is found.

In some occasions, a manufacturer gives the information about a bogie family, namely, a modular chassis that can be configured according to the user's needs. In these cases, the *Observations* field from *general information* table will be filled with "*Flexible family bogies, no concrete data"*. The fields from the other tables will be left in blank unless a field is common for the whole family.

4.3 Classification

The database consists of 5 tables where the information is grouped:

- *general_information*
- *basic_data*
- *braking_system*

- *suspension*
- *frame_properties*

4.3.1 General information

In this table, market information is saved, such as the country where the bogie is in service, the operators that use it, the name that the manufacturer has given, among others.

The following list integrates all the fields found in this table:

- *N_bogie*
- *Name*
- *Manufacturer*
- *Use*
- *Operator*
- *Land*
- *Train_example*
- *Units_in_service*
- *Observations*

The field *Use* has a multiple-choice lookup wizard with the following options: *Tram, Metro, Heavy metro, Regional, Main line, High-speed, Locomotive* and *Freight*. More than one options can be chosen, for instance, *Main line* and *High-speed*.

The fields *Operator* and *Land* also have a multiple-choice lookup wizard. This allows to choose many options due to a bogie is ran in many countries and by many operators.

4.3.2 Basic data

Numerical values of measurements, capacities, weights among others are found in this table. This table defines if a bogie can have an engine, if only exist in trailer mode or both options through a checkbox (Figure 4-3).

The fields in this table are:

- *N_bogie*
- *Motor*
- *Trailer*
- *Wheelset_arrangement*
- *Jacobs*
- *Track_gauge(mm)*
- *Wheelbase(mm)*
- *N_axles*

- *Max_axleload(t)*
- *Weight_motor(t)*
- *Weight_trailer(t)*
- *Max_speed(km/h)*
- *Min_curvature_radius(m)*
- *Observations*

The fields *Motor* and *Trailer* are checkboxes, when both are checked, means that the bogie exists with engine and without. If only one is checked, *Trailer* for example, means that the bogie is not available with the engine, therefore, other fields related to motor bogies will be left blank, *Weight_motor* for example, but also other fields from other tables.

In *Jacobs* field, six options are available: *Yes, No, Option trailer, Option motor, Always trailer* and *Always motor*. Also, a combination of these is possible. For example, if *Option motor* and *Always trailer* are saved, means that the motor bogie can be arranged as a Jacobs but the trailer is always conventional.

N bogie	Motor	Trailer	Wheelset arrangement	Jacobs	Track gauge(mm)	Wheelbase(mm)	N axles	Max axleload(t)	Weight motor(t)	Weight trailer(t)	Max speed(km/h)
1	☑	☑	Bo´Bo´	No	1435	2000	2	14.5	6.7	4.85	80
2	☑	☑	Bo´Bo´	No	1435	2300	2	17	8.5	6.1	120
3	☑	☑	Bo´Bo´	No	1435	2500	2	16	7.2	5.1	90
4	☑	☑ (1)	B´B´	No	1435	2000	2	12	6.6	4.5	80
5	☑	☑	Bo´Bo´	No	1600	2000	2	16	8	5.5	130
6	☑	☑	Bo´Bo´	No	1067	2400	2	17	7.8	5.2	120
7	☑	☑	Bo´Bo´	No	1435	2450	2	22	12.1	8.8	140
8	☑	☑	Bo´Bo´	Option trailer	1435	1060	2	18	7.7	6.5	140
9	☑	☑	Bo´Bo´	Always trailer	1435	2400	2	16	9.5	6.3	160
10	☑	☑	Bo´Bo´	Always trailer	1435	2400	2	20.5	8.9	6.6	200
11	☑	☑	Bo´Bo´	Always trailer	1435	2400	2	18.5	9.2	5.9	200
12	☑	☑	Bo´Bo´	No	1435	2500	2	22.5	12.5	9.4	200
13	☑	☑	Bo´Bo´	No	1435	2700	2	17	9.2	8.8	250
14	☑	☑	Bo´Bo´	No	1435	2700	2	17	8.7	8.5	225
15	☑	☑	Bo´Bo´	No	1435	3000	2	17	11.4	7.2	320
17	☑	☑	Bo´Bo´	No	1435	3000	2	17	83	66	360

Figure 4-3: Fragment of basic_data table. Checkboxes (1)

4.3.3 Braking system

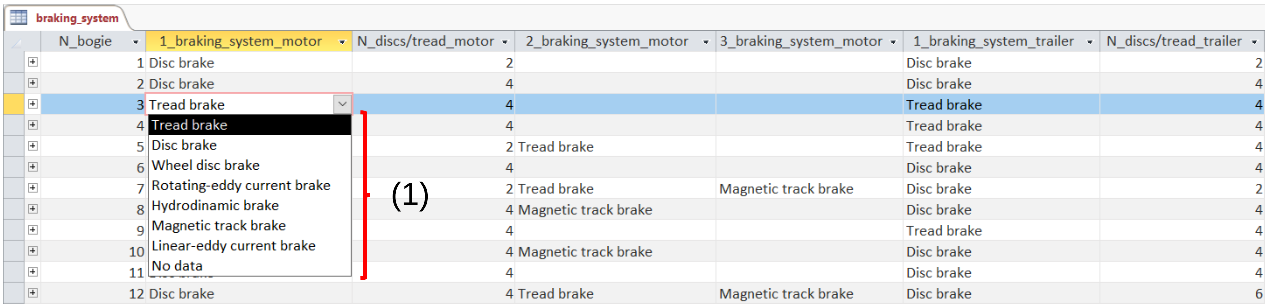
All the possible braking systems explained in the subchapter 3.1 are classified in this table in a simple way. There is a pattern which is repeated twice, once for motor bogies and after for trailer bogies. The pattern is the next: first braking system, number of discs or tread brakes, second braking system and third braking system. The second field is the number of discs or tread brakes. This field is only filled if there are discs or tread brakes in the first braking system field.

According to this pattern, the fields in this table are the following:

- *N_bogie*
- *1_braking_system_motor*
- *N_discs/tread_motor*
- *2_braking_system_motor*

- *3_braking_system_motor*
- *1_braking_system_trailer*
- *N_discs/tread_trailer*
- *2_braking_system_trailer*
- *3_braking_system_trailer*
- *Observations*

The fields *X_braking_system_xxxx* all have a lookup wizard where the systems explained in the subchapter 3.1 are available (Figure 4-4). The *electro-dynamic brake* is not an option because is assumed that all the motor units are provided with. To avoid possible filling errors, the largest number that can be entered in the *N_disc/tread_xxxx* fields is 9. This value can be modified if at any time a bogie with more than 9 units of brake discs/tread bakes is found.


braking_system

N_bogie	1_braking_system_motor	N_discs/tread_motor	2_braking_system_motor	3_braking_system_motor	1_braking_system_trailer	N_discs/tread_trailer
1	Disc brake	2			Disc brake	2
2	Disc brake	4			Disc brake	4
3	Tread brake	4			Tread brake	4
4	[illegible]	4			Tread brake	4
5	[illegible]	2	Tread brake		Tread brake	4
6	[illegible]	4			Disc brake	4
7	[illegible]	2	Tread brake	Magnetic track brake	Disc brake	2
8	[illegible]	4	Magnetic track brake		Disc brake	4
9	[illegible]	4			Tread brake	4
10	[illegible]	4	Magnetic track brake		Disc brake	4
11	[illegible]	4			Disc brake	4
12	Disc brake	4	Tread brake	Magnetic track brake	Disc brake	6

Figure 4-4: Fragment of braking_system *table. Braking systems options (1)*

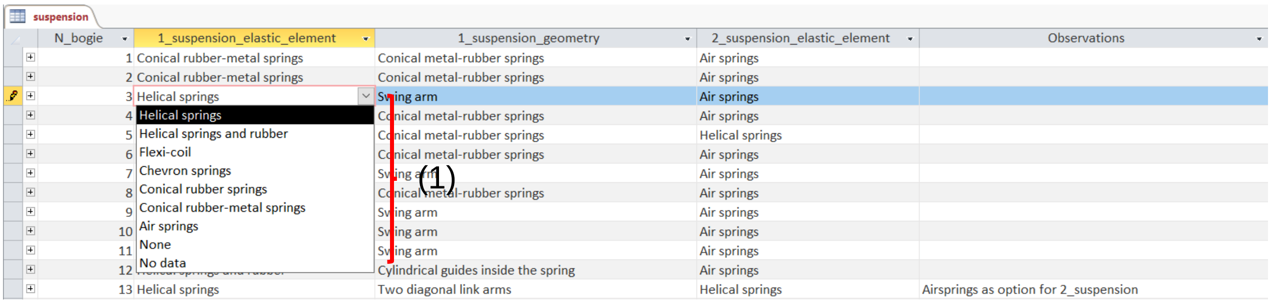
4.3.4 Suspension

All the information about bogies suspension is filled in this table. Because of the suspension is always the same in both trailer and motor bogies, there is no pattern in this table (Figure 4-5). Exceptions will be mentioned in *Observations* field.

Consequently, the fields in this table are:

- *N_bogie*
- *1_suspension_elastic_element*
- *1_suspension_geometry*
- *2_suspension_elastic_element*
- *Observations*

All the fields in this table have a lookup wizard with default options. All the available options are explained in the suspension subchapters 3.3 and 3.4, but not always an option has a subchapter for it. For example, *Chevron springs* and *Conical rubber-metal springs* are different options in the lookup wizard, but both are explained in the same subchapter, 3.3.5 Rubber and rubber-metal springs.


suspension

N_bogie	1_suspension_elastic_element	1_suspension_geometry	2_suspension_elastic_element	Observations
1	Conical rubber-metal springs	Conical metal-rubber springs	Air springs	
2	Conical rubber-metal springs	Conical metal-rubber springs	Air springs	
3	Helical springs	Swing arm	Air springs	
4	Helical springs	Conical metal-rubber springs	Air springs	
5	Helical springs and rubber	Conical metal-rubber springs	Helical springs	
6	Flexi-coil	Conical metal-rubber springs	Air springs	
7	Chevron springs	Swing arm	Air springs	
8	Conical rubber springs	Conical metal-rubber springs	Air springs	
9	Conical rubber-metal springs	Swing arm	Air springs	
10	Air springs	Swing arm	Air springs	
11	None	Swing arm	Air springs	
12	No data	Cylindrical guides inside the spring	Air springs	
13	Helical springs	Two diagonal link arms	Helical springs	Airsprings as option for 2_suspension

Figure 4-5: Fragment of suspension table. Lookup wizard with 1_suspension_elastic_element options (1)

4.3.5 Frame properties

This table stores aspects related to the structure of the bogie and how is it connected to the carbody. Tilting capacity and axle guidance are also saved in this table (Figure 4-2).

- *N_bogie*
- *Chassis_shaped*
- *Frame_shape*
- *Carbody_connection_motor*
- *Carbody_connection_trailer*
- *Tilting*
- *Tilting_system*
- *Axle_guidance*
- *Axle_guidance_system*
- *Observations*

In the *Chassis_shaped* field, it is stored how the chassis has been shaped, the options are: *Welded, Cast, Forged* and *Cast and forged*. This last option is because many bogie frames have some parts which have been forged but also some parts are cast.

The *Frame_shape* field is the one where the shape of the bogie frame is stored. The options available are the ones explained in the subchapter 3.6, *Open-H, Closed-H* and *Three-pieces*.

All possible connections between the carbody and the bogie are available in the fields *Carbody_connection_motor* and *Carbody_connection_trailer*. Depending on whether a bogie is powered or not, its connection may change, for this reason, there are two separated fields, one for the motor bogie and another for the trailer bogies.

In the *Tilting* field, three options are available: *Yes, No* or *No data.* When the bogie has a tilting system, then the next field *Tilting_*system should be filled. It has a lookup wizard with multiple choice. The options are: *Active, Passive, Electric* and *Hydraulic*. As a multiple-choice lookup wizard, a combination of these options is possible. For example, when a bogie has an active tilting system and is electrically actuated, *Active* and *Electric* should be checked.

The *Axle_guidance* work just like the previous one. Three options are available: *Yes, No* or *No data.* When the bogie has an axle guidance system, then the next field *Axle_guidance_system* should be filled. It has a lookup wizard with multiple choice. The options are *Active, Passive, Wheel-rail contact forces* and *Bogie-carbody relative movement*. As a multiple-choice lookup wizard, a combination of these options is possible. For example, when a bogie has a passive axle guidance system and the axlebox is moved by the wheel-rail contact forces, *Passive* and *Wheel-rail contact forces* should be checked.

4.4 Queries

Once the database is filled, information should be extracted from it. This is made by queries. Using a query is possible to answer specific questions about the data that would be difficult to answer by looking directly at the table. Queries can be used to filter, perform calculations, and summarize the data.

The aim of the queries in this thesis is to group the bogies by criteria and analyze which designs are the most common and which has not a market breakthrough, in that specific query. However, the database is a very extensive tool that can be used by other users to extract other information.

5 Results

All the classification, comparison and analysis made in chapter 3 concludes a result of this thesis. The use of this classification as a structure to develop the database explained in chapter 4, shows that the classification works and is ready to be used. The saved bogies in the database are a source of information easy to read.

The database houses 74 bogies, a sample the market, furthermore, 5 queries have been made to prove that it works and see that it is possible to extract results. The queries done are the following:

- Tilting bogies
- Primary and secondary suspension of high-speed bogies
- Axle guidance bogies
- Carbody connections (2 queries)

Tilting bogies query

The criteria for this query are two, *Yes* in *Tilting_system* field, or *High-speed* in *Use* field. The fields shown in the query are:

- *N_bogie*
- *Manufacturer*
- *Use*
- *Train_example*
- *Tilting*
- *Tilting_system*

N_bogie	Manufacturer	Use	Train_example	Tilting	Tilting_system
13	Alstom	High-speed, Main line	No data	Yes	Active, Hydraulic
14	Alstom	High-speed, Main line	No data	Yes	Active, Electric
15	Alstom	High-speed, Main line	No data	No	
17	Alstom	High-speed, Main line	No data	No	
23	Siemens	High-speed, Locomotive	Taurus	No	
31	Siemens	High-speed, Main line	ICE 2	No	
44	Siemens	High-speed, Main line	ICE 3	No	
46	Siemens	High-speed, Main line	ICE TD	Yes	Active, Electric
62	Bombardier	High-speed, Main line	ICE 1	No	
63	Bombardier	High-speed, Main line, Regional	Voyager	No data	
64	Bombardier	High-speed, Main line, Regional	REGINA CRH1	No	

Figure 5-1: Tilting trains query

It is appreciated that there are three high-speed bogies, No. 13, 14 and 46, with inclination capacity, all three are active systems, two are electric systems and the other is hydraulically actuated. It is deduced that a tilting system is not an essential requirement to build a high-speed bogie, it is just a system to provide more comfort, especially when the track is not designed for high-speed trains. As it has been said, Germany and France avoid those systems because of the high cost, instead, these countries design the railway tracks in purpose to non-tilting trains run on them. [42]

Primary and secondary suspension of high-speed bogies

The criterion for this query is high-speed bogies. The fields shown in the query are:

- *N_bogie*
- *Manufacturer*
- *Use*
- *1_suspension_elastic_element*
- *1_suspension_geometry*
- *2_suspension_elastic_element*

N_bogie	Manufacturer	Use	1_suspension_elastic_element	1_suspension_geometry	2_suspension_elastic_element
64	Bombardier	High-speed, Main line, Regional	Helical springs and rubber	Swing arm	Air springs
63	Bombardier	High-speed, Main line, Regional	Conical rubber-metal springs	Swing arm	Air springs
46	Siemens	High-speed, Main line	Helical springs and rubber	Swing arm	Air springs
44	Siemens	High-speed, Main line	Helical springs and rubber	Swing arm	Air springs
31	Siemens	High-speed, Main line	Helical springs and rubber	Cylindrical guides inside the spring	Air springs
17	Alstom	High-speed, Main line	Helical springs	Cylindrical laminated rubber guides outside the spring	Air springs
14	Alstom	High-speed, Main line	Helical springs	Swing arm	Air springs
23	Siemens	High-speed, Locomotive	Helical springs	Two diagonal link arms	Helical springs
13	Alstom	High-speed, Main line	Helical springs	Two diagonal link arms	Helical springs
62	Bombardier	High-speed, Main line	Helical springs	Two parallel horizontal leaf springs	Helical springs and rubber
15	Alstom	High-speed, Main line	Helical springs	Cylindrical laminated rubber guides outside the spring	Helical springs and rubber

Figure 5-2: Primary and secondary suspension of high-speed bogies query

The elastic element of the primary suspension most used in this type of bogies is the helical spring, also combined with rubber elements. It is very probable that those that are classified without rubber elements, they really have, but in the technical sheets of the manufacturer is not mentioned.

The primary suspension geometry more seen in these bogies is swing arm. When it is combined with elastic joints between the arm and the bogie frame, provides passive axle guidance, which is a good property for these bogies due to the superior comfort provided.

Finally, in the secondary suspension, the air springs are the most used for the comfort they provide, beyond this query, not only in high-speed bogies, but in all those that need a good quality driving.

Axle guidance bogies

The criterion for this query is bogies with axle guidance system. The fields shown in the query are:

- *N_bogie*
- *Use*
- *Axle_guidance*
- *Axle_guidance_system*
- *1_suspension_geometry*

N_bogie	Use	Axle_guidance	Axle_guidance_system	1_suspension_geometry
41	Heavy metro	Yes	Passive, Wheel-rail contact forces	Chevron spring
36	Tram	Yes	Passive	Chevron spring
37	Tram	Yes	Passive	Chevron spring
74	Tram	Yes	Passive, Wheel-rail contact forces	Chevron springs
57	Metro	Yes	Passive	Chevron springs
32	Tram	Yes	Passive	Conical metal-rubber springs
43	Heavy metro	Yes	Passive, Wheel-rail contact forces	Conical metal-rubber springs
47	Main line	Yes	Passive, Wheel-rail contact forces	Conical metal-rubber springs
48	Main line	Yes	Passive, Wheel-rail contact forces	Conical metal-rubber springs
40	Heavy metro	Yes	Passive	Conical metal-rubber springs
67	Metro	Yes	Passive, Wheel-rail contact forces	Conical rubber-metal springs
30	Main line	Yes	Bogie-carbody relative movement, Passive	Cylindrical guides inside the spring
31	High-speed, Main line	Yes	No data	Cylindrical guides inside the spring
38	Metro	Yes	Passive, Wheel-rail contact forces	Cylindrical guides inside the spring
39	Metro	Yes	Bogie-carbody relative movement, Passive	Cylindrical guides inside the spring
35	Tram	Yes	Passive	Horizontal leaf springs
68	Freight	Yes	Passive, Wheel-rail contact forces	Horn liner guides
29	Main line	Yes	Passive, Wheel-rail contact forces	Swing arm
51	Main line	Yes	Passive, Wheel-rail contact forces	Swing arm
50	Main line	Yes	Passive, Wheel-rail contact forces	Swing arm
64	High-speed, Main line, R	Yes	Active	Swing arm
34	Tram	Yes	Passive	Swing arm
46	High-speed, Main line	Yes	Active	Swing arm
49	Main line	Yes	Passive, Wheel-rail contact forces	Swing arm
58	Metro	Yes	Passive, Wheel-rail contact forces	Swing arm
52	Main line	Yes	Passive, Wheel-rail contact forces	Swing arm
59	Heavy metro	Yes	Passive, Wheel-rail contact forces	Swing arm
61	Regional	Yes	Passive, Wheel-rail contact forces	Swing arm
44	High-speed, Main line	Yes	No data	Swing arm
45	Main line	Yes	No data	Swing arm
33	Tram	Yes	Passive	Swing arm
23	High-speed, Locomotive	Yes	Passive	Two diagonal link arms
28	Locomotive	Yes	No data	Two diagonal link arms
27	Locomotive	Yes	No data	Two diagonal link arms
26	Locomotive	Yes	No data	Two diagonal link arms
25	Locomotive	Yes	Passive	Two diagonal link arms
24	Locomotive	Yes	Passive	Two diagonal link arms
62	High-speed, Main line	Yes	Bogie-carbody relative movement, Passive	Two parallel horizontal leaf springs

Figure 5-3: Axle guidance query

The query shows that axle guidance is possible with rubber guides such as *chevron springs* and *conical metal-rubber springs.* The other systems have elastic elements on the linking parts to allow axle movement.

The axle guidance system most repeated is passive, concretely the one that moves the axle by the wheel-rail contact forces. That is because of the simplicity of this system in comparison with an active system. Only two bogies, No. 64 and No. 46 have an active system, both are high-speed bogies where comfort should be high, so spending money on a complicated active system is worth it.

Carbody connection

The aim of this query is to find when a bogie has a different carbody connection depending on whether it is a motor or trailer bogie. Therefore, the criterion in this query is *Carbody_connection_motor* field different from *Carbody_connection_Trailer* field. The fields shown in the query are:

- *N_bogie*
- *Manufacturer*
- *Use*
- *Motor*
- *Trailer*
- *Carbody_connection_motor*
- *Carbody_connection_trailer*

N_bogie	Manufacturer	Use	Motor	Trailer	Carbody_connection_motor	Carbody_connection_trailer
15	Alstom	High-speed, Main line	☑	☑	Pivot	Watts linkage
11	Alstom	Regional	☑	☑	Pivot	Traction rod
9	Alstom	Regional	☑	☑	Pivot	Traction rod

Figure 5-4: Carbody connection query

Those three bogies have a central pivot when the bogie is motorized but when it has no engine then the connection is traction rod or Watts linkage. It is deduced that center pivot is a better system to transmit longitudinal forces for motor bogies. This leads to another query to see when the traction rod is used (Figure 5-5). In this extra query, the criterion is *Traction rod* or *Two traction rods* for *Carbody_connection_motor* field. The fields shown are the same as on the Figure 5-4 plus *Max_axleload*.

N_bogie	Manufacturer	Use	Motor	Trailer	Carbody_connection_motor	Carbody_connection_trailer	Max_axleload(t)
10	Alstom	Regional	☑	☑	Traction rod	Traction rod	20.5
18	Alstom	Locomotive	☑	☐	Two traction rods		22.5
19	Alstom	Locomotive	☑	☐	Two traction rods		21.5
20	Alstom	Locomotive	☑	☐	Traction rod		25
21	Alstom	Locomotive	☑	☐	Two traction rods		21.5
22	Alstom	Locomotive	☑	☐	Traction rod		25
26	Siemens	Locomotive	☑	☐	Traction rod		21.5
27	Siemens	Locomotive	☑	☐	Traction rod		23
37	Siemens	Tram	☑	☑	Two traction rods	Two traction rods	10
49	Siemens	Main line	☑	☑	Traction rod	Traction rod	18.5
50	Siemens	Main line	☑	☑	Traction rod	Traction rod	18.5
51	Siemens	Main line	☑	☑	Traction rod		18.5
64	Bombardier	High-speed, Main line,	☑	☑	Traction rod	Traction rod	18.5
66	CRRC	Locomotive	☑	☐	Traction rod		19.5

Figure 5-5: Carbody connection with Traction rod or Two traction rods criteria

Now it is appreciated that traction rods are used mostly to transmit high longitudinal forces for example, for locomotives bogies or heavy metros, moreover, bogies with high axleload like the No. 10, which is not locomotive but because its weight, needs a strong carbody connection.

6 Conclusion and prospect

6.1 Conclusion

This thesis aimed to create a bogie classification, providing a broad overview of its designs without going into concrete parameters, highlighting the advantages and disadvantages of each component design and analyzing how these penetrate on the market. This has been reached by a research of technical railway sources and articles, but also by the creation of a database, a perfect tool to compare.

This thesis can be used to have an overview of how a bogie will behave according to how it has been arranged, namely, which components have been chosen for a function. Moreover, the classification allows selecting which is the ideal component for a specific feature, furthermore, the database will confirm if the selection is widely used in the market.

To summarize, the dynamic behavior of the bogies is determined by the multiple combinations of its components, a specific selection will specialize the bogie for a concrete function. Today's technology has managed to reach very high levels of optimization, weight reduction, even without harming the comfort, but sometimes the simplest solution is the most efficient either by manufacturing costs or efficiency.

6.2 Prospect

Regarding the classification done, the most used and modern designs have been analyzed, however, not all the component designs are explained in this thesis, for example, a classic crossbow suspension is not mentioned at any time. This is because this thesis has focused on the most avant-garde components from modern bogies, with a deep interest in high-speed and comfort designs, without focusing on those obsolete or very reduced-use.

A possible improvement would be to introduce a weight criterion to select which design is better compared to others, this would be useful to get weight reduction. Considering that many components such as dampers, brakes and carbody connections, are steel components and can hardly be replaced by other material, it is necessary to focus on the bogie frame shape or bogie frame material to reach weight reduction. Furthermore, the suspension is also susceptible to being revised, as it has been explained in suspension chapters, it is not always made of metal parts.

Should not be forgotten that each component is a broad topic and could have an own thesis for itself, so this thesis could be the introduction for a future deep investigation of a concrete component.

To obtain a broader vision of the diversity of bogies in the market, and get closer to reality, it is necessary to expand the database with more bogies, a task explained in chapter 4. Moreover, new fields can be added, for example, dampers types and dampers arrangement, which are now mentioned on *Observations* field due to the lack of information in the technical data sheets. The more fields and bogies the database is completed with, the more useful will be.

The relation between wheel wear due to the wheel-rail contact forces and axle guidance systems is a possible topic to analyze. Not all the manufacturers explain which solutions they develop to face this phenomenon. However, the technical data sheets sometimes explain which is the diameter of a new wheel and which is the minimum diameter that can be reached by wear. A compromise between equipping a suitable axle guidance system (to reduce wear) and a periodical wheel replacement should be reached.

A List of Figures

B References

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